

Spectral and human sensors

Hyperspectral remote sensing and participatory
GIS for mapping livestock grazing intensity and
vegetation in transhumant Mediterranean
Conservation areas

Jane Bemigisha

Promotors:

Prof. Dr. A.K. Skidmore
Professor of Vegetation and Agricultural Landuse Survey
International Institute for Geo-Information Science and Earth Observation
(ITC), Enschede, The Netherlands

Prof. Dr. H.H.T. Prins
Professor of Resource Ecology, Wageningen University, Wageningen, The
Netherlands

Co-promotors:

Dr. S.E. van Wieren
Assistant Professor, Resource Ecology Group, Wageningen University, The
Netherlands

Examining Committee:

Prof.dr. E.M.A. Smaling, Wageningen University, The Netherlands

Dr. H.H. de Iongh, Leiden University, The Netherlands

Prof. P. Pilesjo, Lund University, Sweden

Prof. K. Dabrowska Zielinska, University of Warsaw, Poland

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Production Ecology and Resource Conservation (PE & RC), Wageningen
University, The Netherlands

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*To my dear girls Joan, Leira and Phyllis,
your uncles Johnson and James,
your "Shwenkulu" , late "Mukaaka and resting aunties and uncle"*

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Summary

Increasing shortage of pasture resources due to land use conversion constitutes a major challenge to traditional transhumance systems. Reduction of transhumance and related activities leaves the non converted areas abandoned. This may lead to change in grazing intensity, which might result into change in species composition and vegetation pattern. A reduction in grazing intensity might thus influence the biodiversity and forage quality of previously more intensively grazed areas. Proper management of Mediterranean grasslands would require insight on how grazing intensity varies across a landscape and how it influences the distribution and abundance of plant species.

The aim of this study was to investigate methods for mapping of livestock grazing intensity and vegetation, using hyperspectral remote sensing, geographic information systems (GIS) and participatory GIS (PGIS). Investigations were undertaken at two main levels. A greenhouse experiment was used to investigate the effects of defoliation and defoliation time for two species grown in mono and mixed culture on the height and dry matter yield as measures of regrowth and competitive ability of two livestock forage grasses selected from a transhumant Mediterranean area. Narrow band hyperspectral reflectance, indices and the red-edge position were investigated to see if they may be used to study these effects. At field landscape level, we tested the use of local people's knowledge in mapping grazing intensity through the application of PGIS.

The results from the greenhouse experiment showed that the species with higher dry matter yield (*Lolium multiflorum*) had a significantly higher relative regrowth rate and possibly higher competitive ability than its competitor *Dactylis glomerata* ($P < 0.05$). Increase in dry matter yield was shown as the trait that determines competitive ability in the early established stage of the two grass species (period of 13 to 18 weeks after sowing). The experiment also provided insight on the persistence of forage species that are of grazing preference. Selective clipping did not alter the competitive ability of *D. glomerata* to surpass that of *L. multiflorum* when the former was clipped at lower clipping intensity to simulate selective grazing.

The hyperspectral remote sensing variables that may be used to estimate the effect of species types, cultures and defoliation treatments were: the physiological reflectance index (PRI), the Carter index, R_{694} , the ration of the Transformed Chlorophyll Absorption in Reflectance Index to the Optimized Soil-Adjusted Vegetation Index

(TCARI/OSAVI) and the red-edge position. The PRI was found to be the most sensitive index. A significant increase ($p < 0.001$) in PRI was associated with the higher competitive ability of *L. multiflorum* than *D. glomerata* when the two were mixed. The response of the PRI from negative to positive over the measurement time in relation to height and dry matter yield suggest that the PRI may be used to study competitive ability because the related growth characteristics are indicators of competitive ability. This encourages further investigation of this method as a potential simpler and quicker alternative to the existing canopy height and pasture growth models. This may lead to efficient assessment and improved understanding of the condition and spatial patterns of forage vegetation species at field level.

At field landscape level, using participatory GIS (PGIS), spatial knowledge on grazing intensity from pastoralists and local range ecology experts was elicited and relevant criteria generated and used to classify grazing intensity. Local pastoralists appeared to be more knowledgeable than local range ecology experts, possibly because of the pastoralists' superior familiarity with the rangeland and better perceptions about the distribution of palatable species but the experts represented the grazing intensity better on a map. Local pastoralists have potential to contribute better to this process if the PGIS includes adequate training in the map making process. The local experts showed the capability to produce data and synthesize spatial variables, but it was also shown that the expert-based PGIS maps may not always be reliable. Using a proposition that "*This area or pixel belongs to the high, medium, or low grazing intensity class because the local expert(s) says (say) so*", we tested for uncertainty in the PGIS-maps produced by different local experts using spatial tools such as evidential belief functions (EBFs).

Evaluating the classification uncertainty in the different grazing intensity maps revealed that the maps with the lowest uncertainty were based on the composition of palatable vegetation species as the mapping criterion. This criterion may be used for mapping grazing intensity because it relates to measures of forage condition such as ground cover and quality, but it may be limited in use if other parameters such as vegetation composition and quantity are not integrated. If the definition of grazing intensity also includes these parameters and also livestock vegetation use factor and impacts on vegetation, then the proposition for EBF evaluation would be that: "*This pixel or area is a specific grazing intensity class because of the level of livestock grazing use and its impacts on species composition, ground cover, quantity and quality*". These parameters may be

efficiently estimated using hyperspectral remote sensing. In order to include local knowledge in such an evaluation, research should establish how local pastoralists and experts may process the various parameters and how they may apply such a proposition.

Since more than one criterion proved cumbersome for the local experts as evidenced by a weak correlation between the grazing intensity map and a grazing suitability index ($r = 0.35$ ($p < 0.01$)), spatial multiple criteria tools may be useful for synthesizing the different mapping criteria.

Overall, this study showed that high spectral resolution sensors can detect the effect of grazing and competitive interactions among forage plants through narrow band channels across the spectrum, while the local people perceive a few broad grazing intensity classes and spatially represent them using a few criteria. The two are complementary. The spectral sensor provides detailed information on the status and spatial patterns of vegetation, while local participants provide the spatial information on a more general coarse scale that may be used as baseline for hyperspectral remote sensing research.

Samenvatting

De afname van weidegronden door landgebruiksverandering vormt een belangrijke uitdaging voor traditionele transhumance systemen. Een afname van de transhumance en daaraan geassocieerde activiteiten kan ook leiden tot het verlaten van die gebieden waar het land gebruik niet veranderde. Dit kan leiden tot een verandering in begrazingsintensiteit wat op haar beurt weer kan leiden tot een verandering in soortsamenstelling en vegetatie patronen. Een vermindering van de begrazingsintensiteit zou dus invloed kunnen uitoefenen op de biodiversiteit en gewaskwaliteit in voorheen meer intensief begraasde gebieden. Beheer van Mediterrane graslanden heeft behoefte aan inzicht hoe begrazingsdruk varieert over een landschap en hoe dit de verspreiding en abundantie van planten soorten beïnvloedt.

Het doel van deze studie was het onderzoeken van methodes voor het karteren van vegetatie en begrazingsdruk door vee, gebruik makend van aardobservatie, geografische informatie systemen (GIS) en participatoire GIS (PGIS). Het onderzoek had twee niveaus. Een kasexperiment werd gebruikt om de effecten van defoliatie te onderzoeken op twee gras soorten geselecteerd uit een transhumant mediterraan gebied. Het experiment testte voor mono en mixed cultures van beide soorten de effecten van intensiteit en frequentie van defoliatie op de hoogte en droge stof opbrengst. Verder testten wij of nauwe band hyperspectrale reflectie en daarvan afgeleide indices en red edge positie bruikbaar zijn om deze effecten van defoliatie te detecteren. Op landschapsniveau testten wij de bruikbaarheid van de kennis van lokale bevolking voor het karteren van begrazingsintensiteit door middel van participatoire GIS.

Het kasexperiment toonde aan dat de soort met een hogere initiële droge stof opbrengst (*Lolium multiflorum*) een significant hogere relatieve hergroei snelheid ($p < 0.05$) en mogelijk een hoger competitief vermogen had dan zijn concurrent *Dactylus glomerata*. Aangehouden werd dat toename in droge stof opbrengst de eigenschap is die het competitief vermogen van beide soorten in de vroege vestigingsfase (13 tot 18 weken na het zaaien) bepaald. Het experiment gaf ook inzicht in de hardnekkigheid van geprefereerde gras soort. Selectieve defoliatie bracht geen verandering teweeg in het competitief vermogen van met mate gedefolieerde *D. glomerata* ten opzichte van intensiever gedefolieerde *L. multiflorum*.

Voor het detecteren van het effect van soorten en het defoliatie regime maakten wij gebruik van de volgende hyperspectrale remote

sensing variabelen: de fysiologische reflectie index (PRI), de carter index, R_{694} , de ratio TCARI / OSAVI en de positie van de red edge. De PRI bleek de meest gevoelige index te zijn. Een significante ($p < 0,001$) toename in PRI was geassocieerd met het hogere competitieve vermogen van *L. multiflorum* in vergelijking met *D. glomerata* wanneer de twee gemixt werden. De relatie van de PRI, die toenam van negatief naar positief gedurende de duur van het experiment, met de hoogte en droge stof opbrengst suggereert dat de PRI gebruikt zou kunnen worden voor het bestuderen van competitief vermogen omdat de gerelateerde groei karakteristieke indicatoren zijn voor competitief vermogen. Deze bevinding stimuleert verder onderzoek van de potentie van deze methode als een simpeler alternatief voor bestaande vegetatiehoogte en weide groei modellen. Dit zou kunnen leiden tot efficiëntere schatting en verbeterd begrip van de conditie en de ruimtelijke patronen van weide soorten.

Participatoire GIS (PGIS) technieken werden gebruikt om bij pastoralisten en lokale ecologische experts aanwezige kennis aan het licht te brengen, vooral ruimtelijke kennis over graasdruk en relevante criteria voor het classificeren van graasdruk. Lokale pastoralisten bleken meer kennis te bezitten dan lokale ecologische experts, waarschijnlijk ten gevolge van hun betere kennis over de conditie van de weidegebieden en hun betere perceptie van de verspreiding van eetbare soorten. De ecologische experts representeerden de graasdruk echter beter op een kaart. De lokale pastoralisten hebben potentie om bij te dragen aan het maken van kaarten als de PGIS adequate training zou geven in het karteringsproces. De lokale experts toonden capaciteit in het produceren van data en het synthetiseren van ruimtelijke variabelen, maar er werd ook aangetoond dat de PGIS kaarten gemaakt door experts niet altijd even betrouwbaar waren. Wij testten de onzekerheid van de PGIS kaarten geproduceerd door verschillende experts gebruik makend "evidential belief functions (EBF)" en van de stelling dat "*dit gebied of deze pixel behoort tot de klasse met hoog, medium of laag graaspotentieel omdat de lokale expert dat zegt*".

Evaluatie van de classificatie onzekerheid van de verschillende graas intensiteit kaarten bracht aan het licht dat de kaarten met de laagste onzekerheid gebaseerd waren op de samenstelling van eetbare soorten als criterium. Dit criterium kan gebruikt worden voor het karteren van graas intensiteit omdat het gerelateerd is aan gewas conditie zoals bedekking en kwaliteit maar de bruikbaarheid zou gelimiteerd kunnen blijken te zijn als er geen gebruik wordt gemaakt van andere variabelen zoals vegetatie samenstelling en de biomassa. Indien de definitie van graasintensiteit ook deze variabelen omvat

evenals de gebruiksfactor door vee en de invloed op de vegetatie dan zou de stelling voor EBF evaluatie kunnen luiden: "*deze pixel of dit gebied behoort tot een specifieke graas intensiteit klasse vanwege het niveau van begrazing en haar impact op soortsaamenstelling, grondbedekking en kwaliteit en biomassa*". Deze variabelen zouden efficiënt geschat kunnen worden met behulp van hyperspectrale remote sensing. Om te komen tot integratie van lokale kennis in zo'n evaluatie zou verder onderzoek uit moeten wijzen hoe lokale pastoralisten en experts deze variabelen verwerken. Omdat het gebruik van meer dan een criterium lastig bleek voor de lokale experts, wat werd aangetoond door een zwakke correlatie tussen de graas intensiteit kaart en een begrazing geschiktheids index ($r=0.35$, $p<0.01$), zouden ruimtelijke multipale criteria systemen geschikt kunnen zijn om de effecten van meerdere criteria te synthetiseren.

Samenvattend heeft deze studie aangetoond dat hoog spectrale resolutie sensoren gebruik makend van nauwe en specifieke spectrale banden verdeeld over het spectrum het effect van begrazing en competitieve interacties tussen soorten kunnen detecteren, terwijl de lokale bevolking een aantal brede graas intensiteit klassen waarneemt en gebruik makend van een beperkt aantal criteria in staat is om de verspreiding van deze begrazing intensiteit klassen ruimtelijke weer te geven. Deze twee methodes zijn complementair. De spectrale sensor geeft gedetailleerde informatie omtrent de status en de ruimtelijke patronen van de vegetatie terwijl de lokale bevolking op een grovere schaal meer algemene informatie kan verschaffen die bruikbaar is als baseline voor het hyperspectrale remote sensing onderzoek.

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CHAPTER 1

General introduction

1.1 Why study livestock grazing intensity and vegetation in transhumant Mediterranean conservation areas?

The European Forum for Nature Conservation and Pastoralism (EFNCP) has in recent decades been debating the future of transhumance and its functions (Bignal, 1998; Fortina *et al.*, 2000). The transhumance referred to in this research is largely characterised by pastoralists' movements to higher elevations during summer (May-June) and to lower elevations in winter (October-November). Declining forage resources is a key challenge to maintaining transhumance in some Mediterranean countries in Europe such as Italy, Spain and Portugal (Bignal, 1998; Susmel, 2004). This has been due to the intensification of other landuse functions, as well as the economically driven abandonment of free-ranging pastoral livestock grazing (Bignal, 1998; Bignal and Pienowski, 1999; Fortina *et al.*, 2000). The main alternative landuse function that has been introduced is nature conservation (Bunce *et al.*, 2004; Pienowski and Bignal, 1999).

Combining livestock grazing and wildlife conservation helps to maintain the livestock keepers' livelihoods (Prins *et al.*, 2000; Smart *et al.*, 1985; Stevens, 1997; Voeten, 1999) while using the livestock grazing as a vegetation management tool for increasing productivity of the forage species (Van Wieren, 1996; Voeten, 1999; Prins and Nell, 1990). The combination also helps to promote plant communities valuable for biodiversity conservation (Bakker, 1989). Any reduction in transhumance activities in order to cater for conservation, however, may lead to spatial changes in grazing intensity ranging from high to low intensity. This might result in change in species composition and vegetation patterns (Andrew, 1988; Bakker, 1989). Proper management of these transhumant Mediterranean areas would, therefore, require understanding of how grazing intensity varies in a landscape and how it influences the distribution and abundance of plant species (Gutman *et al.*, 2001; Turner, and Hiernaux, 2002).

Innovations in vegetation mapping show that remote sensing and geographic information systems (GIS) may improve the understanding of the distribution of vegetation resources and livestock feeding impacts (Skidmore *et al.*, 2005). Hyperspectral remote sensing, specifically, offers possibilities to estimate different forage parameters such as species composition, species quality and quantity at fine spectral, spatial and temporal scales (e.g., Armitage *et al.*, 2000; Mathur *et al.*, 2002). At the same time, the use of knowledge from local pastoralists (e.g., Davis, 2005; Rasmussen *et al.*, 1999; Turner and Hiernaux, 2002) and local experts (e.g., Van der Hoeven *et al.*, 2004) may contribute to the mapping of various biophysical parameters because local people usually have intimate and long term knowledge of their ecological environment (Gonzalez, 2002). Yet further improvement stems from using participatory GIS (PGIS), because of the additional functionality of spatial representation of this knowledge (Rambaldi *et al.*, 2006).

The use of these new geo-information tools and different knowledge sources in estimating grazing intensity and associated forage plant response and competitive ability has not, however, been fully investigated. In this research, therefore, the use of hyperspectral remote sensing, GIS and PGIS for mapping livestock grazing intensity and vegetation in transhumant Mediterranean conservation areas is investigated.

1.2 Effect of grazing intensity on vegetation

Grazing intensity in this research refers to the level of defoliation by livestock grazing and browsing. The term *grazing* is used to include grazing and browsing. Clipping has been used to simulate different levels of defoliation that may also be associated with defoliation by cutting (e.g., cutting hay) and grazing by wild herbivores that are not subject of this research. Defoliation is one of the factors that affect plant growth and condition (Grime, 1979). Defoliation influences plant productivity in contrasting ways. For example, while intensive defoliation through grazing has resulted in reduced population density of some plant species (e.g., Noy-Meir and Briske, 1996), other species have compensated for defoliation damage by increasing production (e.g., Boyd and Svejcar, 2004; Cooper, 1964; Loud *et al.*, 1990; Riba, 1998; Wolfson, 1999).

Studies show that the effect of defoliation on vegetation is influenced by the competitive characteristics of co-occurring plant species (Espigares *et al.*, 2004; Humphrey and Schupp, 2004; Owen-Smith, 2002a). Competition results if individuals of a species experience reduced growth as a result of unfavourable resource exploitation such as light, water, and soil nutrients or when there is interference by another species (Owen-Smith, 2002b; Tilman 1988). This means that even in the absence of defoliation, plant species affect each other's growth (Tilman, 1988). Therefore, the growth performance of forage plants may also be affected by competition, necessitating the understanding of competition in livestock forage species while studying grazing intensity and its effects on vegetation. Importantly, the competitive ability of plant species preferred for grazing may depend on their growth rate versus that of their non-preferred neighbours (Fetene, 2003; Noy-Meir, 1990). Therefore, if research on the effect of grazing on vegetation has to include competitive interactions among forage species, particular attention should be placed on the performance of the preferred species.

1.3 Estimating the effect of grazing intensity on vegetation

1.3.1 Conventional methods

In the previous section, it is seen that the effect of defoliation on vegetation is influenced by competitive interactions among forage plant species. The competitive interactions may be investigated by determining competitive ability of individual plant species. *Competitive ability* has been defined and determined in various ways. According to Goldberg (1990), the competitive ability of a plant may be determined based either on the competitive effect, that is, the ability of an individual to suppress other individuals, or on the competitive response, which refers to the ability of an individual to avoid being suppressed, corresponding to different abilities of plants to acquire and use resources. A number of traits such as plant or leaf height, leaf size, biomass, etc., are known to influence this ability (Goldenberg, 1996).

Related definitions (e.g., Tilman, 1988; Gause 1934) describe competitive ability considering the relative rate of increase in abundance and ability to competitively displace other species from a specific habitat. This may be determined using the de Wit replacement series (e.g., Dayan *et al.*, 1981; Dovrat *et al.*, 1980; Noy-Meir and Briske, 2002; Tilman, 1988; Loo, 1993). In this approach, relative yields of two species (often yields of above ground

biomass) grown at different relative densities are used. In addition to the relative yield of above ground biomass, Grime (1979) identifies plant growth characteristics that determine competitive ability such as plant height, lateral spread and growth rate. However, research is needed to establish the specific traits that determine competitive ability of different co-occurring forage species so as to minimize research time and effort.

Competitive ability of forage plant species in response to defoliation may be determined by the regrowth capacity, i.e., renewed growth of leaves, expansion of new shoots (Grime, 1979), and shoot density (e.g., Lenssen *et al.*, 2004). This research has focused on regrowth in plant height and weight (dry matter yield) of co-occurring forage grasses.

Of the characteristics that determine competitive ability, growth rate which is a product of dry matter yield, has been found to play a vital role in plant competition (e.g., Damgaard, 1999; Humphrey and Schupp, 2004). This influence is usually pronounced during the early stages of growth (Tilman, 1988). Growth rate is used in terms of relative growth rate (RGR) and associated components such as unit leaf rate, specific leaf area, and leaf weight (e.g., Hunt *et al.*, 2002). Relative growth rate is defined by Hunt (1978) as an increase in the dry weight of plant material per unit of the material and per unit of time.

A variable that is often contrasted with dry weight in measuring plant performance is shoot height (e.g., Pronk *et al.*, 2007; Wallace and Verhoef, 2000). Plant height influences competitive ability because it affects the ability of a plant to compete successfully for light (Grime, 1979). Studies (e.g., de Wit, 1965) have shown that height is of competitive advantage during early establishment stage. This is because the species that grows taller usually captures more incident light, photosynthetic efficiency, and consequently suppresses other plants. This means a plant species that attains higher height may also be considered a better competitor. Consequently, studies on defoliation also include height as a measure of plant performance (e.g., Navas and Moreau-Richard, 2005). Therefore, it is difficult to identify which growth characteristics may be used to determine competitive ability. Therefore, for efficient investigation of competitive ability and grazing intensity, an *a priori* investigation on whether to use dry matter yield or plant height is needed.

The term *grazing intensity* is also defined and used in different ways. For example, livestock grazing intensity may be estimated based on livestock numbers such as animal units (AU)/ha (Heitschmidt and

Stuth, 1991), stocking density (Verweij, 1995), and stocking rate (Morris *et al.*, 1999; Rasmussen *et al.*, 1999). Other authors (e.g., Kawamura *et al.*, 2005) include vegetation resources and the environmental factors as suggested by Bakker (1989). Bakker (1989) suggests estimating grazing intensity by using terrain use or occupancy from direct observation or counting, occupancy from dunging intensity, foraging utilization, forage condition and quantity.

For efficient estimation of grazing intensity, Bakker's characterization of grazing intensity by vegetation condition, quantity and foraging utilization (Bakker, 1989) may be used. This is because these variables are consistent with the remote sensing variables of relevance to rangeland management, such as fractional green herbaceous cover, fractional senescent herbaceous cover, above-ground biomass, and canopy height. The use of remote sensing in capturing these variables helps to reduce the time and labour traditionally needed for field surveys, and also provides timely and objective information over extensive rangeland areas (Tueller, 1989). The estimation of these variables has improved through mapping of herbivore forage quality, quantity and distribution by use of hyperspectral remote sensing (e.g., Mutanga and Skidmore, 2004). What has not been adequately investigated, however, is canopy height which may help in estimating defoliation intensity. The integration of competitive interactions among forage species is also rare. In the current research, using hyperspectral remote sensing to study defoliation intensity and competitive interactions among forage species is, therefore, adding new insights to the remote sensing framework.

1.3.2 The potential of hyperspectral remote sensing

The basis for remote sensing application to vegetation studies is the association of spectral reflectance in vegetation with chemical, physiological and biophysical properties (e.g., Fillella and Penuelas, 1994; Knipling, 1970; Mutanga and Skidmore, 2007; Patel *et al.*, 2001). According to Figure 1.1, green leaf biochemical properties including water, photosynthetic pigments, and structural carbohydrates create wavelength-specific absorption features in the visible part of the spectrum (400 nm to 700 nm). The adjacent Near Infrared (NIR) region (700 – 1300 nm) is characterized by strong reflection of infrared radiation by mesophyll tissue (Campbell 2002). In NIR, leaf morphology (e.g., cell wall thickness, air spaces, cuticle wax) affect photon scattering (Jensen, 2007; Clark *et al.*, 2005). In the longer infrared (beyond 1300 nm), leaf water content controls the spectral properties. Water accounts for the absorption spectrum of a

leaf at 1400 nm to 2500 nm (Campbell, 2002). Between the visible and infrared regions is the red-edge position (680 - 750 nm) defined as the wavelength of maximum slope and found to be independent of chlorophyll concentration, effects of species, developmental stage, leaf layering and leaf water content (Horler, 1983).

The Red and NIR bands have important application to plant growth and vegetation condition monitoring because as the plant grows to maturity and senescence, reflectance begins to decrease in the NIR and increase in the Red region (Campbell, 2002). This makes spectral vegetation indices such as the normalized difference vegetation index (NDVI) $(NIR - Red / NIR + Red)$ appropriate for monitoring such changes. The index is based on the highly contrasting chlorophyll pigment absorptions in the red region against the high reflectivity of plant materials in the NIR region (Tucker, 1979).

Canopy level properties are associated with vegetation tissue optical properties (leaf, woody stem, and standing litter), canopy biophysical attributes (e.g., leaf and stem area, leaf and stem orientation, foliage clumping), soil reflectance, illumination conditions, and viewing geometry (Asner, 1998; Noy-Meir and Briske, 2002). Canopy properties such as height may be important for estimating defoliation intensity, since this has been one of the problems for using remote sensing in rangeland assessment studies (1989). The canopy height attributes can be derived through inversion of models involving a bidirectional reflectance distribution function (BRDF) which is difficult to extract, especially from conventional broad-band remotely sensed spectral data (Chopping, 2003).

Recent studies use narrow band spectral variables by use of hyperspectral remote sensing. Hyperspectral remote sensing refers to the use of high spectral resolution sensors comprising numerous contiguous bands and channels of less than 10 nm (Campbell, 2002). The terminologies used to describe the techniques differ depending on specific applications (Kumar *et al.*, 2001). This research applied spectroscopy which involves detailed examination of very accurate spectral data by use of spectroradiometers, spectrometers, etc., to extract surface spectral reflectance from collected radiation (Campbell, 2002). The term *hyperspectral remote sensing*, which includes the application of spectroscopy to image analysis is used in this study to imply the integration of data from a spectroradiometer and HyMap image data as well as the utility of the outcomes for further study at laboratory experiment and field landscape level.

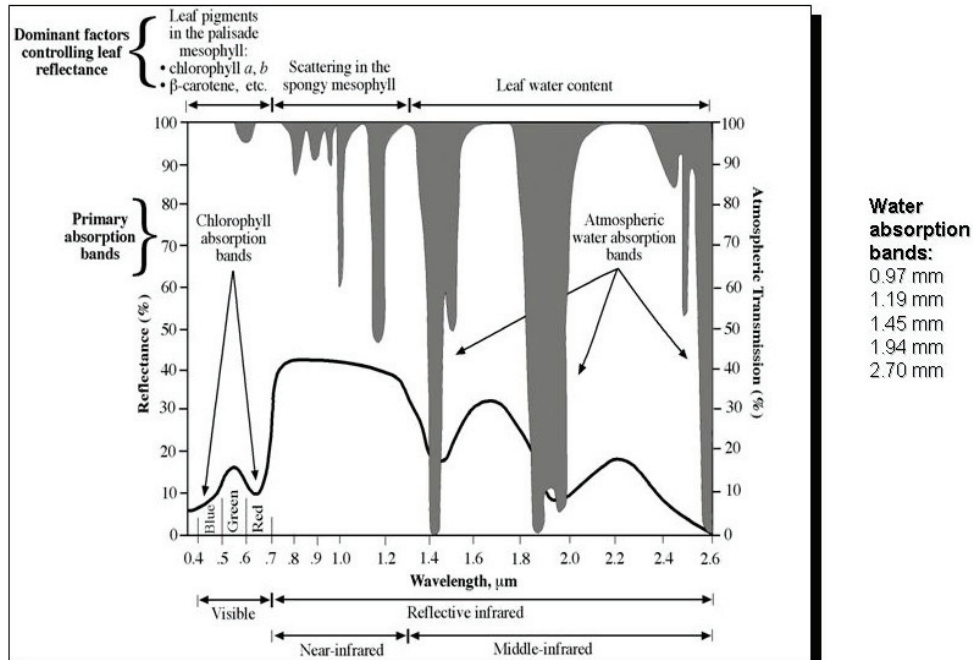


Figure 1.1 Factors controlling reflectance of a green leaf (source: Jensen, 2007)

Based on the large number of contiguous narrow bands, hyperspectral sensors obtain vast quantities of detailed information on spectral characteristics of an object which would otherwise be 'lost' within the relatively coarse bandwidths acquired with multispectral sensors (Curran, 1994; Goetz 1985; Thenkabail *et al.*, 2000). The fine discrimination between different targets based on their spectral response in the narrow bands has helped in better estimation of different vegetation parameters such as species composition, species quality and quantity at fine spectral, spatial and temporal scales (e.g., Armitage *et al.*, 2000; Mathur *et al.*, 2002; Mutanga *et al.*, 2003; Schmidt and Skidmore, 2001). These and the various studies that have specifically explored spectral indices for detecting grazing impacts and plant growth modelling (e.g., Alvaro *et al.*, 2007; Aparicio *et al.*, 2000; Chopping, 2003; Numata *et al.*, 2007; Sims and Gamon, 2002) have rarely included competitive interactions among forage species.

Narrow-band spectral features may be used to study grazing intensity and competitive interactions among forage species if the spectral features are related to the vegetation variables that are affected by

these two factors. For example, the narrow band NDVI ($R_{830} - R_{670}/R_{830} + R_{670}$) and the Simple Ratio (R_{830}/R_{680}) have been associated with biomass (e.g., Alvaro *et al.*, 2007; Mutanga and Skidmore 2004). The association of NDVI and SR with growth crop traits such as leaf area per plant (LAP), green area per plant (GAP) and plant dry weight at different growth stages suggests the use of spectral reflectance measurements in assessing growth traits of individual plants (Alvaro, *et al.*, 2007). In addition, the Carter index ($R_{695} \text{ nm} / R_{760} \text{ nm}$) has been associated with plant stress, while the PRI ($(R_{531} - R_{570}) / (R_{531} + R_{570})$) is associated with radiation use efficiency, and changes in leaf nitrogen and leaf area index (LAI) (Barton and North, 2001; Peñuelas *et al.*, 1994; Peñuelas *et al.*, 1995). These indices relate to the physiological and biophysical parameters of vegetation that may be affected by defoliation and competition in forage plants.

An additional feature of interest is the red-edge position (680 nm to 750 nm) which is strongly correlated with biochemical concentration in plants especially leaf Nitrogen and chlorophyll content (Horler *et al.*, 1983). The red-edge has been used for estimating biomass and LAI (e.g., Cho *et al.*, 2006; Fillella and Peñuelas, 1994; Mutanga and Skidmore, 2007). In this research, therefore, narrow band spectral data were tested for use in estimating the effect of defoliation intensity and determining competitive ability of co-occurring forage plant species.

1.3.3 The value of local knowledge and spatial mapping tools

Studies that integrate different kinds of knowledge and technologies are motivated by improved content, complementarity of the different knowledge sources and higher quality through cross validation of different knowledge products (e.g., Close, 2005; Gobin *et al.*, 2000; Ho and Smith, 1997; Van der Hoeven *et al.*, 2004; Walker *et al.*, 1999; Verlinden and Dayot, 2005; Wynne *et al.*, 2007). For example, local knowledge may contribute to valuable information for scientific resource assessment (Close and Hall, 2006).

There are many forms of local knowledge. "Local ecological knowledge (LEK)" or "indigenous ecological knowledge" in this research is used synonymously with the commonly used term "local knowledge". LEK is based on not only a person's general knowledge of nature but also specific local understanding adapted to the culture and environment, and it is not static (Yli-Pelkonen and Kohl, 2005). Some scholars (e.g., Close, 2005) question the application of this knowledge in conventional scientific investigations but acknowledge

its increasing contribution in the representation of people's knowledge at localized spatial scale. This contribution is most valuable when data based on empirical studies are limited or are not available (e.g., Ho and Smith, 1997; Store and Kangas, 2001; Van der Hoeven *et al.*, 2004). Since the effects of free-ranging and herded livestock are not fully understood because of limited spatial data (Turner and Hiernaux, 2002), this research included an investigation on the use of local knowledge in mapping livestock grazing intensity. Two types of local knowledge were investigated: (a) from local pastoralists, (b) from local range experts.

A number of researchers have recognized that knowledge from local pastoralists is a vital source of information for rangeland management (e.g., Davis, 2005; Rasmussen *et al.*, 1999; Turner and Hiernaux, 2002; Verweij, 1995). In absence of baseline data, local pastoralists' knowledge may play an important role in the understanding of spatial distribution of grazing intensity and vegetation because of their familiarity with the rangelands and foraging behaviours of their herds (Gonzalez, 2002). For example, Turner and Hiernaux (2002) have mapped grazing intensity based on local livestock keepers' knowledge of land use patterns, topography, vegetation, settlements and water points.

Local experts also contribute valuable knowledge to scientific ecological studies (e.g., Van der Hoeven *et al.*, 2004; Prins and Wind, 1991). Expert knowledge is based on data and information from a person with a recognized profession, techniques, skill or knowledge of a specific subject as a result of experience through practice and education. Local range expert knowledge or rangeland expert knowledge as used in this study therefore represents knowledge obtained from rangeland experts, park managers, researchers and consultants working locally with Majella National Park, the field study area. They are termed "local" because of their proximity and interaction with the rangelands and grazing activities.

One of the problems that have been faced while using local knowledge in ecological assessments is spatial representation. Mapping approaches based on local knowledge are focused on the use of participatory GIS (PGIS) to spatially collect, organize and analyze this knowledge (e.g., Rasmussen *et al.*, 1999; Turner and Hiernaux, 2002). The tools and methods differ from GIS and conventional participatory information collection such as participatory rural appraisals (PRA). For example, while GIS is efficient in data capturing, storing, editing, integrating, analyzing and presentation, its limitations in mapping details of land use and management, are

recognized. Therefore, PGIS offers a solution to spatial representation of local knowledge and was used in this research to obtain and represent spatial information on grazing intensity.

The question that PGIS-based mapping has not addressed adequately is ascertaining the reliability of the map products. For the application of PGIS in grazing intensity mapping, the problem may be that there are various factors that influence the spatial distribution of livestock grazing intensity, and local people may find it difficult to disaggregate the numerous spatial factors (Jansen, 1998). This may lead to classification uncertainty. This problem may be solved by use of spatial multicriteria evaluation (SMCE). SMCE includes GIS functions of data acquisition, storage, retrieval, manipulation and analysis as well as techniques for evaluating and aggregating the geographical data and standardizing various decision preferences (Malczewski, 1999). SMCE, however, does not offer possibilities to adequately represent uncertainty.

The evaluation and representation of classification uncertainty may be handled by use of Bayesian theory and modified related theories such as the use of evidential belief functions (EBFs) and Dempster's rule of combination. These tools have been used to evaluate uncertainty in geospatial classification problems (e.g., Kim and Swain, 1989; Solaiman *et al.*, 1998; Moon, 1990; An *et al.*, 1994b; Carranza and Hale, 2002). EBFs and Dempster's rule of combination were, therefore, investigated in this research for evaluating uncertainty in classification and for integrating different PGIS-based maps of grazing intensity.

1.4 Aim and objectives of the thesis

The aim of this study is to investigate methods for mapping of livestock grazing intensity and to capture competitive interactions among forage vegetation species, using hyperspectral remote sensing, GIS and PGIS. The first objective is to investigate the effects defoliation intensity, species cultures (mixed or monoculture) and species type on biophysical vegetation variables (height and dry matter yield). This is used to determine competitive ability of selected forage grass species and to investigate whether hyperspectral remote sensing may be used to study these. The second objective is to examine the use of local people's knowledge in grazing intensity mapping at field landscape level.

1.5 The scope of the study

Ecologists consider systems as organized at different hierarchical levels, such as cells, organisms, populations, communities, ecosystems (Rietkerk et al., 2002). Processes and patterns can therefore be understood and described if based on cross-scale observations or modelling (Rietkerk et al., 2002) and examined at different levels of assessment (e.g., Mutanga, 2004). The kinds of knowledge and geospatial tools reviewed in the previous sections, therefore, may be applied at different spatial and temporal scales and levels of investigation. This research comprises three forms of investigation using different geospatial technologies (hyperspectral remote sensing, GIS and PGIS) and different kinds of knowledge, making use of a laboratory experiment and field landscape investigations.

A laboratory experiment was set-up in a greenhouse at the Wageningen Plant Sciences Experimental Centre, Wageningen University, in the Netherlands. In this experiment, there were two investigations. First, we tested for effects of different clipping time, clipping intensities, species cultures and species type on the growth traits (regrowth in dry matter yield and height) in order to determine the competitive ability of two co-occurring livestock forage grass species. The two species, *Dactylis glomerata* and *Lolium multiflorum*, were identified in Majella National Park, Italy, the field study area (section 1.6). The species were grown in either mixed or monocultures, and clipped at varying heights above the ground, that is, 5 cm (high clipping intensity), 10 cm (medium clipping intensity) and 15 cm (low clipping intensity). We assumed the effects to be interactive in a nested form. This means that each of the species occurred in either mixed or monocultures, and were clipped at varying intensities at different clipping events. Therefore, a nested Analysis of Variance model was used, whereby clipping time was nested within the interaction effect of species type, species culture and clipping intensity (Figure 1.2).

Preferred species in mixed vegetation communities are vulnerable especially if their co-occurring neighbours are less affected by comparatively less intensive grazing (Lenssen *et al.*, 2004; Noy-Meir, 1990). In this experiment, the effect of selective clipping on the regrowth and competitive ability of the selected forage grass species to simulate selective grazing was included.

Competitive ability was determined through regrowth capacity following Grime (1979), based on re-sprouted plant tissue clipped or

removed between clipping intervals. In contrast to the functional or dynamic approach, we calculated regrowth in shoot weight and height across one harvest interval (i.e., the period of time between the two successive harvests T2 and T3), as used by Hunt *et al.* (2002). A five-week interval was used following Hannaway *et al.* (1999). The relative regrowth rate was calculated as the difference in the mean of the natural log of dry weight at the two clipping intervals. This definition differs from the definition of relative growth rate given in other literature (e.g., Hoffman and Hendrik, 2002), because we considered only the growth increment minus remaining stubble at the previous time of clipping. Height regrowth was defined as the difference between the average plant height at clipping T2 and T3.

Emphasis was put on the two growth characteristics of dry matter yield and height because they are key variables that show competitive ability in plants (Grime, 1979) and at the same time relate to spectral measurements (section 1.3.2).

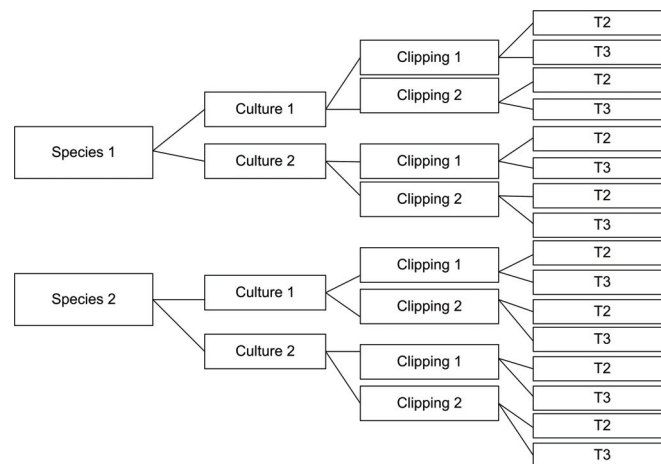


Figure 1.2 The nested ANOVA model showing clipping time nested in clipping height nested in culture and species. Species 1 and 2 are *D. glomerata* and *L. multiflorum*; Culture 1 and 2 are monoculture and mixed culture, respectively; Clipping 1 and 2 are for Low (15 cm clipping height) and High (10 cm clipping height); T2 and T3 are clipping events at 13 weeks and 18 weeks after sowing, respectively.

Investigating grazing intensity and competitive dynamics in various co-occurring forage species at field level would require intensive research that may be costly. Remote sensing approaches that help to obtain information at fine spectral, spatial and temporal scale may

provide the information detail, content and frequency of observation needed. Moreover the biophysical variables that indicate competitive ability such as height and dry matter yield can be efficiently studied using hyperspectral remote sensing. Therefore, the second component of the experiment explored the potential of hyperspectral remote sensing (Section 1.3.2) for estimating defoliation intensity and determining competitive ability.

While hyperspectral remote sensing may be useful for estimating defoliation intensity and determining competitive ability, the contribution of knowledge from other sources may be complementary (see section 1.3.3). At field landscape level, the use of local people's knowledge (local pastoralists and experts) for grazing intensity classification through the application of participatory GIS (PGIS) was investigated. The study was undertaken in Majella National Park, Italy, described in section 1.6. The investigation was focused on ascertaining the ability of local participants in scoping and using spatial variables or criteria for mapping grazing intensity. The integration of different participatory maps and representation of classification uncertainty was made using evidential belief functions (EBFs) and Dempster's rule of combination (Dempster, 1967; Shafer, 1976) based on a proposition that "*This area or pixel belongs to the high, medium, or low grazing intensity class because the local expert(s) says (say) so*".

The ability of the local participants in grazing intensity classification was tested by comparison of the PGIS-based maps with a SMCE-based grazing suitability index. To test the relationship between a grazing distribution map obtained from the PGIS and a grazing suitability index, the hypothesis was that the livestock grazing intensity classification map derived from local experts correlates well with a grazing intensity classification map derived by integrating landscape-level factors such as terrain, landuse and vegetation that influence livestock grazing intensity. The assumption was that the local experts are familiar with the rangeland patterns and levels of grazing intensity as is found in other pastoralist societies (Gonzalez, 2002). Expert knowledge products have also been used in similar ecological studies (Van der Hoeven *et al.*, 2004; Prins and Wind, 1991)"

1.6 The study area

The study was undertaken in Majella National Park, which covers 740 km² in a Mediterranean mountainous area located in eastern Italy (UTM Zone 33 N: 411235m E, 4634626m N; 433155m E, 4674766m N)

N) (Figure 1.3). The mountain ranges that comprise Majella National Park form part of the Italian Apennines. The prominent peaks in the park are Mt. Morrone and Mt. Majella, which are located on either side of the park. Between Mt. Majella in the east and Mt. Morrone in the west, the park is traversed from north to south by valleys and floodplains of the River Orta and River Orfento. The highest peak of the Majella rises to about 2800 m. About 38% of the area extends to 1500 m above sea level. Majella National Park is part of the wider Abruzzo protected area system (the shaded region containing the park shown in the inset of Figure 1.3).

Livestock grazing has been the main land use in Majella since about 2000 BC. The grazing activities in Majella National Park and most of the surrounding region are declining following the park gazettelement in 1995. In addition to reduced grazing to cater for conservation, there were numerous economic migrations in the 1950s that led to the abandonment of local agricultural activities, including transhumant livestock grazing. About 32 pastoralists are registered to graze sheep, cattle, goats and a few horses in the park on a transhumance basis (spring-summer season). The land is hired by the park from either the municipalities or the church and allocated to the pastoralists on a rental basis. This allocation has, however, not been demarcated, and the boundaries are not enforced.

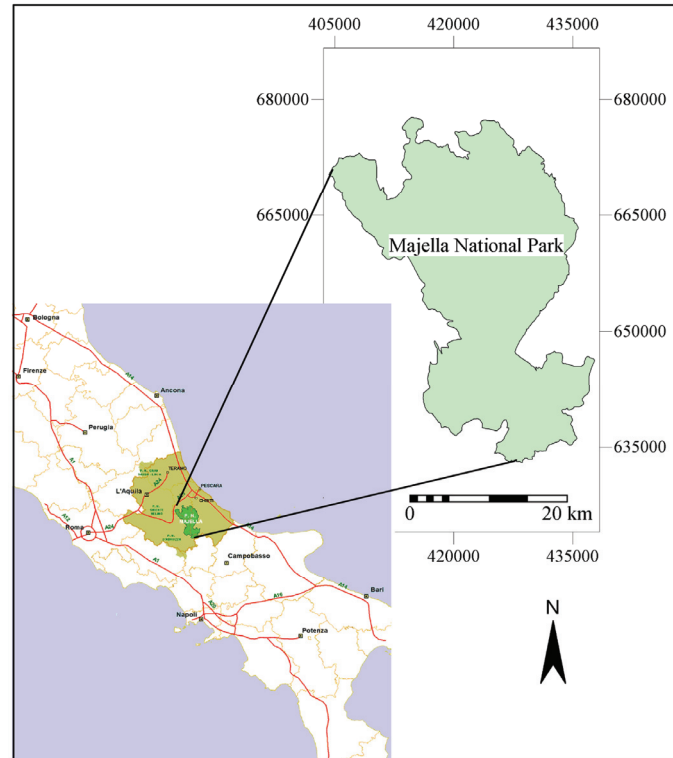


Figure 1.3 Location of Majella National Park in Italy

The pastoralists fall into two categories: a few residents and the majority regional transhumant pastoralists. The resident pastoralists keep the livestock in barns and cut hay during winter. In contrast, the regional transhumant pastoralists ascend the mountains with their herds to graze during summer (May-June) and descend back to warmer areas in winter (October-November). The regional pastoralists keep the livestock in temporary overnight rotational shelters. The herds are usually on the range from 8.00 a.m. to 7.00 p.m. Watering is mainly by streams and wells with troughs. There are also a few ranches in the northern (Pestoconstanza) and southern (de Contra) parts of the area.

Vegetation changes in Majella from grassland to shrubs and forest may be attributed largely to the abandonment of cultivation fields and the reduction in grazing. According to Cho (2007), the abandoned areas seem to be changing to oak (*Quercus pubescenes*) woodlands at the lower altitude (400 m to 600 m) and beech (*Fagus sylvatica*) forest at the higher altitude (1200 m to 1800 m). These are interspersed by shrubby bushes, patches of grass/herb and bare rock

outcrops. Therefore, with the continuing reduction in livestock grazing in the park, the mountain pastures may increasingly change into coarse grasses with fewer herbs, while the lower-level hay/meadow areas may change into woody scrub (Pienowski and Bignal, 1999). These changes may not be distributed evenly and the effect of the current livestock grazing intensity on vegetation in the different parts of the park is not known.

1.7 Thesis structure

This thesis comprises five papers, four of which have been prepared for journal publication and one presented at a conference. The papers are based on laboratory and field levels of investigation.

1.7.1 Laboratory level

Following this introduction, Chapters 2 and 3 cover a clipping laboratory experiment to investigate the regrowth in height and dry matter, as well as the competitive ability of two forage grass species, under the effect of defoliation, species type and species cultures (monoculture and mixed). The effect of selective grazing on the regrowth and competitive ability of the species is also tested. Based on the same experiment, narrow band spectral reflectance, indices and the red-edge position are investigated for application to studying the effects indicated in the previous chapters. The spectral variables that are most sensitive to the different species and clipping treatments are recommended for application at field level (Chapter 4).

1.7.2 Field level

At field level, the use of local knowledge from pastoralists and experts is investigated (Chapter 5). Using participatory geographic information systems (PGIS), local spatial data on grazing intensity was obtained and relevant criteria generated and used to classify grazing intensity. The utility of evidential belief functions (EBFs) to represent uncertainty and establish the reliability of the PGIS-based grazing intensity maps, and a new application of Dempster's rule of combination to integrate five different maps was demonstrated. Livestock grazing intensity classification by local experts is further investigated in relation to a livestock grazing suitability index obtained from a combination of spatial factors considered to determine grazing intensity. The use of local people's knowledge in identifying and synthesizing different criteria for grazing intensity classification is tested. Spatial data integration and the analysis tools used, in particular EBFs and spatial multicriteria evaluation (SMCE),

are found helpful in verifying the reliability of PGIS products through integration and testing to establish the consistency and use of local knowledge.

In the final chapter (Chapter 6), the conceptual research framework is presented together with the main conclusions.



CHAPTER 2

Effect of clipping intensity on growth traits and competitive ability of forage grass

Based on: Jane Bemigisha, Sip E. van Wieren, Andrew, K. Skidmore, Alfred Stein, and Jan de Leeuw. (In review after revision, Grass and Forage Science). Initial growth and competitive ability of *Dactylis glomerata* and *Lolium multiflorum* in a clipping experiment

Abstract

The objective of this study was to establish how different intensities of defoliation affect growth characteristics and competitive ability of livestock forage grasses (*Lolium multiflorum* and *Dactylis glomerata*) at an early growth stage. A clipping experiment was set-up in a greenhouse at the Plant Sciences Experimental Center, Wageningen University and Research (WUR), in the Netherlands. The two species were grown in either mixed or monocultures and clipped three times at two five-week intervals. A nested Analysis of Variance (ANOVA) was used to test for effects of species type, species culture (monoculture or mixed), clipping height, and clipping time on plant height and dry matter (DM) yield of the two grasses. We found that clipping had greater effect on height than on dry matter yield, but increase in DM yield showed a stronger positive linear relationship with relative regrowth rate ($RRR = 0.0008 + 0.0143 * x$ ($p < 0.05$, $r^2 = 0.96$) than with height. Dry matter yield was also the dominant growth characteristic in monocultures for *D. glomerata*, and in mixed cultures for *L. multiflorum*. *L. multiflorum* showed a significantly higher relative regrowth rate than *D. glomerata* ($P < 0.05$), suggesting higher competitive ability. Our results conform to the notion that competition depends largely on growth rate. Further research may test this approach for understanding the effects of defoliation and species mix in forage grass species under livestock grazing and hay cutting considering various growth traits and environmental situations.

2.1 Introduction

Defoliation influences the growth and competitive interactions in forage plants (Grime, 1979). The effect of defoliation in the early established phase may significantly affect the competitive ability and survival of co-occurring forage species (e.g., Johnson *et al.*, 1983). The competitive ability of a plant may be studied based either on the competitive effect, implying the ability of an individual to suppress other individuals, or on the competitive response, implying the ability of an individual to avoid being suppressed, which relates to different abilities of plants to acquire and use resources (Goldberg, 1990). Tilman (1988) attributes the uncertainty surrounding predictions of competitive response and effect in the early stages of plant growth to the transient dynamics, which may be comparable to those in eventual vegetation patterns (e.g., Berendse *et al.*, 1992). Research is therefore required on the short-term vegetation dynamics in the early established stages of plant growth (Goldberg, 1996; Tilman, 1988).

In interaction with defoliation, the uncertainty of the competitive response in forage plants may increase. For example, research on the combined effect of competition and grazing (e.g., Center *et al.*, 2005; Flower and Rausher, 1985; Ilmarinen *et al.*, 2005; Millett *et al.*, 2005; Kuijper *et al.*, 2004; Loo, 1993; Olff *et al.*, 1999; Rodriguez and Brown, 1998; Vesik and Westoby, 2001) shows that these effects are not easily predicted because of the variable environmental context such as temperature, water, light and soil (e.g., Dayan *et al.*, 1981; Hardegree and Van Vactor, 1999; Höglind *et al.*, 2001; Pronk, *et al.*, 2007; Tilman, 1988; Riba, 1998), as well as various plant traits. Defoliation may change the ability of a plant to acquire limited resources such as soil nutrients and light by altering key morphological traits (Loud *et al.*, 1990).

Grime (1979) identifies the characteristics determining the competitive ability of plant species in the early established phase to be storage organs, height, lateral spread, phenology, growth rate, response to stress, and response to damage. A more elaborate list of plant traits that have been correlated with competitive ability is provided in Goldberg (1996). Goldberg (1996) indicates that different studies show different predictions about traits correlated with competitive ability (Goldberg, 1996). Since the competitive traits differ among plant species, then the plant species' capacity to regrow following damage caused by defoliation may also differ. The capacity to regrow may also be influenced by defoliation intensity. Studies on interactions of competition and defoliation have shown

that defoliation height is important (Loo, 1993). For example, following defoliation, re-initiation of the leaves of grasses at the base of the tiller forms subsequent leaf growth, depending on whether the leaf-forming meristems are low enough to escape damage (Langer, 1979). There is, therefore, need to identify traits that most correlate with competitive ability of specific plant species under different defoliation intensities.

Plant height is widely used in estimating competitive ability of plants because it is associated with the ability of a plant to compete successfully for light (Grime, 1979; Wallace and Verhoef, 2000). Height is particularly important during the initial growth stages because plants that become taller faster obtain a disproportionate share of the incident light, enhance their photosynthetic efficiency, and thus suppress the growth of other individuals (Tilman, 1988; de Wit, 1965). Pronk *et al.* (2007), however, suggest that plants may co-exist through different height growth strategies. This is related to the hypothesis that plant types with different heights can persistently co-exist over longer periods of time despite the competitive interactions (Pronk *et al.*, 2007). Therefore, a plant that grows taller may be considered a better competitor but this may not be consistent in all plant species and it is not easy to predict the persistence of this trait. This means that in spite of various investigations on plant height in response to defoliation and competition (e.g., Burboa-Cabrera *et al.*, 2003; Boyd and Svejcar, 2004; Navas and Moreau-Richard, 2005), research is still needed to estimate the extent to which plant height determines competitive ability.

Plant weight (biomass) and size are also widely used to determine competitive ability (Damgaard, 1999; Riba, 1998). Some studies show that larger plants have a higher absolute growth rate (Damgaard, 1999; Fetene, 2003; Riba, 1998). Competition however, seems to depend largely on growth rate, which is a product of dry weight (Tilman, 1988). Growth rate among species is expressed as relative growth rate and is commonly used to measure plant performance, including cases of defoliation (e.g., Damgaard, 1999; Humphrey and Schupp, 2004; Johnson *et al.*, 1983; Loo, 1993; Osem *et al.*, 2004). Relative growth rate is an increase in plant material per unit of material and per unit of time (Hunt, 1978). This means that a species that attains higher dry weight over a given time may be considered a better competitor. Since plant height may also determine competitive ability, this chapter focuses on both plant height and the weight (dry matter yield) of co-occurring forage grasses.

In a greenhouse experiment, we investigated the effects of species type, species culture, clipping height, and clipping time on the increase in height and dry matter yield of *Lolium multiflorum* and *Dactylis glomerata* in the early established phase of one growing season (vegetative stage). By comparing the increase in the height and dry matter yield with regrowth rate, we established the dominant competitive growth characteristic. The species that increased more in the dominant growth characteristic consistent with a high relative regrowth rate in mixed cultures was considered to have a higher competitive ability.

2.2 Materials and methods

2.2.1 Study species

The two forage grass species, *L. multiflorum* and *D. glomerata*, that were selected occur in Majella National Park, Italy, the study site related to this research (Chapter 5), where hay-cutting and grazing of livestock and wild animals combine. The two species are livestock forage grasses and widely used for hay. They have competitive growth characteristics. *L. multiflorum* (Annual ryegrass) is an annual or sometimes biennial bunch grass with a fibrous root system. It grows 30 to 100 cm tall. *L. multiflorum* is a highly palatable and digestible grass (Hannaway *et al.*, 1999). It is also known for its high yield potential, rapid establishment, and it is commonly used on heavy waterlogged soils (Hannaway *et al.*, 1999). On the other hand, Duke (1983) describes *D. glomerata* (Orchard grass or Cocksfoot grass) as a tufted fast-growing perennial, with a deep root system. It grows 20 to 120 cm tall. It grows rapidly, enabling it to out-compete most of the other plants. *D. glomerata* also thrives best on heavier types of soils such as clay and clay-loams, although it can also survive well in poor dry soils, and is drought-resistant. It is known to withstand heavy grazing (Cullen *et al.*, 2006), and gives a good aftermath if cut for hay (Duke, 1983). Under continuous heavy grazing, however, the persistence of *D. glomerata* declines significantly (Duke, 1983; Avery *et al.*, 2000) and, if under-grazed, it becomes coarse and unpalatable (Duke, 1983).

2.2.2 Experiment set-up

2.2.2.1 Description of pot soils and seeding

D. glomerata and *L. multiflorum* seeds were sown on 14 December 2004 in a greenhouse at the Plant Sciences Experimental Center, Wageningen University and Research Center (WUR), in the Netherlands. Pots of 23 cm in diameter and 5 litres in volume were

used. Potting soil was fertilized with 12.4%, phosphorous 14.2%, and potassium 13.8%. In each pot, we used a broadcast method to sow 40 seeds of either monoculture or a mixed culture. For the pots containing mixed cultures, 20 seeds of each species were sown.

2.2.2.2 Design of treatments and replicates

Altogether there were 18 replicates for each of the following twelve treatments: three combinations of species (monoculture of the two species and mixed culture) and four clipping heights (none, 5 cm, 10 cm, and 15 cm). The resulting 216 pots were placed according to a 6x6 design (Figure 2.1).

Clipping height levels were determined following Boyd and Svejcar (2004) and were maintained for all the clipping intervals. In this analysis, 10 cm and 15 cm are the clipping heights used for high and low clipping intensity, respectively, to simulate defoliation at low and high intensity.

H1	N2	L3	M1	H2	N3		L1	M2	H3	N1	L2	M3
N2	L3	M1	H2	N3	L1		M2	H3	N1	L2	M3	H1
L3	M1	H2	N3	L1	M2		H3	N1	L2	M3	H1	N2
M1	H2	N3	L1	M2	H3		N1	L2	M3	H1	N2	L3
H2	N3	L1	M2	H3	N1		L2	M3	H1	N2	L3	M1
N3	L1	M2	H3	N1	L2		M3	H1	N2	L3	M1	H2
7							8					
L1	M2	H3	N1	L2	M3		H1	N2	L3	M1	H2	N3
M2	H3	N1	L2	M3	H1		N2	L3	M1	H2	N3	L1
H3	N1	L2	M3	H1	N2		L3	M1	H2	N3	L1	M2
N1	L2	M3	H1	N2	L3		M1	H2	N3	L1	M2	H3
L2	M3	H1	N2	L3	M1		H2	N3	L1	M2	H3	N1
M3	H1	N2	L3	M1	H2		N3	L1	M2	H3	N1	L2
5							6					
H1	N2	L3	M1	H2	N3		L1	M2	H3	N1	L2	M3
N2	L3	M1	H2	N3	L1		M2	H3	N1	L2	M3	H1
L3	M1	H2	N3	L1	M2		H3	N1	L2	M3	H1	N2
M1	H2	N3	L1	M2	H3		N1	L2	M3	H1	N2	L3
H2	N3	L1	M2	H3	N1		L2	M3	H1	N2	L3	M1
N3	L1	M2	H3	N1	L2		M3	H1	N2	L3	M1	H2
3							4					
L1	M2	H3	N1	L2	M3		H1	N2	L3	M1	H2	N3
M2	H3	N1	L2	M3	H1		N2	L3	M1	H2	N3	L1
H3	N1	L2	M3	H1	N2		L3	M1	H2	N3	L1	M2
N1	L2	M3	H1	N2	L3		M1	H2	N3	L1	M2	H3
L2	M3	H1	N2	L3	M1		H2	N3	L1	M2	H3	N1
M3	H1	N2	L3	M1	H2		N3	L1	M2	H3	N1	L2
1							2					
						↑						
						Entrance						

Figure 2.1 Set-up and treatment codes in the greenhouse. Clipping intensity treatments: L = Low, M = Medium, H = High, N = None; subjects (species): 1 = *L. multiflorum*, 2 = *D. glomerata*, 3 = mixed (*L. multiflorum* and *D. glomerata*).

2.2.2.3 Growing conditions

The grasses were planted in a greenhouse with environmental conditions imitating the summer growing season of Majella National Park, Italy: day temperature 20°C and night temperature 15°C; natural daylight and additional light from 400 W AGRO-SON-T Phillips lamps to provide 16 hours of light; outdoor humidity; normal air; and adequate watering. The greenhouse conditions were set at the same level to ideally demonstrate competitive ability given the same natural habitat as may be for naturally co-occurring species following a strategy used in the Zone of Influence (ZOI) model (Gates, 1980). In the ZOI model equivalent resources are distributed uniformly over an area in the analysis of competition (Gates, 1980).

2.2.3 Clipping treatments and measurements

Clipping was done at five-week intervals, starting on 3 February 2005. The intervals were at T1: eight weeks, T2: 13 weeks and T3:18 weeks after sowing following Hannaway *et al.* (1999), and a later review (Cullen *et al.*, 2006). Before clipping, the average height of grass plants in each pot was obtained from measurement with a metric ruler against leaves in a pulled upright form. In the mixed cultures, separate height measurements were taken for each species. The clipped plant material was dried at 70°C for three hours and at 105°C for another 10 hours. As in height measurement, the weight of the dried matter was measured per unit (pot), maintaining separate weight for each species in the mixed cultures. Prior to analysis, the dry weight of monocultures (sown with 40 seeds) was divided by two to enable comparison with mixed cultures (20 seeds of each of the two species). Table 2.1 presents the data on height (cm) and dry matter (g).

2.2.4 Analysis

Using a nested analysis of variance (ANOVA) in STATISTICA by StaSoft Inc., USA, we investigated the effect of species type (*Dactylis* and *Lolium*), species culture (monoculture and mixed), clipping height and time of clipping on the increase in height and dry matter yield of *L. multiflorum* and *D. glomerata*. In a nested analysis, levels of one factor occur in combination with the levels of one or more other factors, and different levels occur in combination with others at the next level (Zar, 1996). For this study, the species have different levels of cultures, and the cultures have different levels of clipping height, while clipping was at three different times (T1, T2 and T3). Figure 2.2 illustrates the nested model used in this study. Only

variables of T2 and T3 were used in the analysis because T1 was the base clipping time. Table 2.1 shows the mean height (cm) and dry matter (g) according to the analysed factor levels. Rather than the functional or dynamic approach (e.g., de Wit *et al.*, 1978; Tilman, 1988), a simpler approach was used by calculating growth parameters (dry matter yield (g) and height (cm) across one harvest interval as done in Hunt *et al.* (2002).

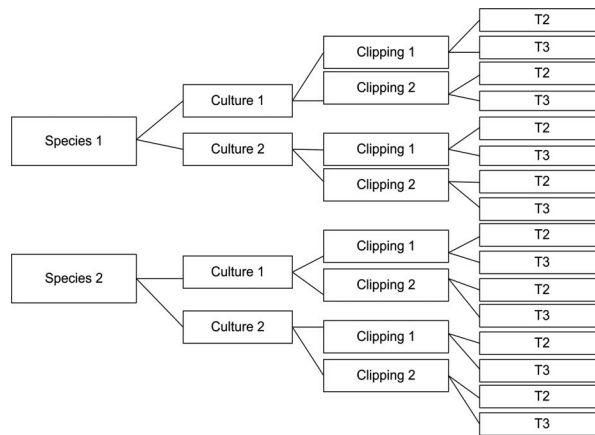


Figure 2.2 An illustration of the nested ANOVA model used. Clipping time nested in clipping height nested in culture and species. Species 1 and 2 are *D. glomerata* and *L. multiflorum*; Culture 1 and 2 are monoculture and mixed culture respectively; Clipping 1 and 2 indicate Low (15 cm) and High (10 cm); T2 and T3 indicate clipping at 13 weeks and 18 weeks after sowing, respectively.

The following model indicates that the effect of clipping time is nested within the interaction effects of species × culture × clipping height.

$$G = (\text{Species} * \text{Culture} * \text{Clipping}) / \text{Time}$$

The following terms are used to express the model:

$$G_{ijknl} = (\text{Species}_i * \text{Culture}_j * \text{Clipping}_k) \text{Time}_n + e_{ijknl} \quad (\text{Eq.2.1})$$

where:

- G_{ijkl} = the mean growth response variable, i.e., height or dry weight
- Species_{*i*} = *D. glomerata* (for *i* = 1) and *L. multiflorum* (for *i* = 2)
- Culture_{*j*} = monoculture (for *j* = 1) and mixed culture (for *j* = 2)
- Clipping_{*k*} = clipping height, i.e., low clipping at 15 cm height (for *k* = 1) and medium clipping at 10 cm height (for *k* = 2)
- Time_{*n*} = T2 and T3, i.e., clipping time interval 2 (13 weeks after sowing) (for *n* = 1) and clipping time interval 3 (18 weeks after sowing) (for *n* = 2)
- e_{ijknl} = a normally distributed error term with mean zero.

The effect was considered significant at $P \leq 0.05$, and if $F_{Observed} > F_{Expected}$. A Scheffé *post hoc* test using $P = 0.05$ significance level was used to establish the specific pairs of treatments that significantly differed from each other.

We established the competitive ability by using relative regrowth rate (RRR) based on the relative growth rate formula (Hoffman and Hendrik, 2002):

$$RRR = \frac{\overline{\ln(W_3)} - \overline{\ln(W_2)}}{t_3 - t_2} \quad (\text{Eq.2.2})$$

where $\overline{\ln(W_2)}$ and $\overline{\ln(W_3)}$ are the mean of the natural log of dry weight at two clipping dates, t_2 and t_3 . The RRR is the difference in the mean of the natural log of dry weight at the two clipping intervals. Our definition includes only the growth increment minus remaining stubble at the previous time of clipping (dry matter (g) of re-sprouted plant tissue clipped or removed between clipping intervals)), which differs from relative growth rate. Height regrowth was defined as the difference between the average plant height at clipping T2 and T3.

To establish the species that showed higher competitive ability and the growth characteristic that was more consistent with relative regrowth rate, a paired *t*-test was used to test for differences between regrowth in height versus regrowth in dry matter yield, regrowth in height versus relative regrowth rate, and regrowth in dry matter yield versus relative regrowth rate. Scatter plots were used to show the relations.

Table 2.1 Mean height (cm) and mean dry matter (DM g) with 95% confidence intervals for species, *D. glomerata* and *L. multiflorum* in monocultures and mixed cultures under low intensity (15 cm height) and high intensity clipping (10 cm height), clipped at T2: 13 weeks after sowing and T3: 18 weeks after sowing.

T2: 13 weeks after sowing

Species	Culture	Clipping height (cm)	Average height (cm) (n = 18)			DM (g) (n = 18)		
			Ht (cm)	-95%	+95%	DM (g)	-95%	+95%
<i>D. glomerata</i>	Mixed	15	29.41	27.63	31.20	9.09	8.41	9.77
		10	28.50	26.76	30.22	8.67	7.99	9.36
	Mono-culture	15	37.56	35.77	39.34	6.66	5.98	7.34
		10	36.58	34.85	38.32	7.11	6.64	8.00
<i>L. multiflorum</i>	Mixed	15	32.03	30.25	33.81	12.2	11.49	12.85
		10	30.33	28.60	32.06	11.5	10.86	12.22
	Mono-culture	15	32.03	30.25	33.81	6.21	5.53	6.89
		10	29.25	27.52	30.98	7.37	6.68	8.05

T3: 18 weeks after sowing

Species	Culture	Clipping height (cm)	Average height (cm) (n = 18)			DM (g) (n = 18)		
			Ht (cm)	-95%	+95%	DM (g)	-95%	+95%
<i>D. glomerata</i>	Mixed	15	32.29	30.64	33.95	9.16	8.61	9.70
		10	31.18	29.50	32.83	8.76	8.23	9.29
	Mono-culture	15	37.72	29.11	32.33	7.91	7.36	8.45
		10	36.33	34.72	37.94	8.51	7.98	9.04
<i>L. multiflorum</i>	Mixed	15	33.12	31.44	37.76	13.4	12.91	14.00
		10	31.82	30.17	33.48	13.6	13.09	14.15
	Mono-culture	15	30.72	29.11	32.33	6.98	6.46	7.51
		10	31.00	29.39	32.61	7.54	7.01	8.07

2.3 Results

2.3.1 Effect of clipping and species on height

We tested for the effects of clipping time, clipping height, species cultures and species on height and found that the effects were highly significant (Table 2.2). The results from the nested ANOVA showed that height was significantly affected by species ($F_{12, 264} = 31.56$; $P < 0.001$), culture ($F_{12, 264} = 43.05$; $P < 0.001$), clipping ($F_{12, 264} = 8.3$; $P < 0.005$), and time nested within these interactions ($F_{12, 264} = 8.23$;

$P < 0.001$). Figure 2.3 shows the mean height (cm) for *D. glomerata* and *L. multiflorum* in mixed cultures and monocultures and clipping intensity at 15 cm height and 10 cm height above the ground. The letters on top of the bars show significance of the differences between pairs according to the Scheffé *post hoc* test. Comparing the increase in height of the two species, the mixed cultures of *D. glomerata* under both low (15 cm) and high (10 cm) clipping heights was lower than that of *L. multiflorum*, but in the monocultures the reverse was true. Between T2 and T3, the mean height in both mixed cultures and monocultures of *D. glomerata* clipped at low clipping height increased significantly ($P < 0.05$), but this was not the case with the higher clipping height.

On the other hand, the *L. multiflorum* monoculture under low clipping showed a decrease in height, whereas under high clipping an increase was shown. Table 2.1 shows the mean height with 95% confidence intervals. *L. multiflorum* showed 4% higher average height than *D. glomerata* in mixed cultures at T2 and the difference was significant ($P < 0.05$), but the difference at T3 was only 2%. In the monocultures, height in *D. glomerata* was 12% higher than that of *L. multiflorum* and the difference was significant ($P < 0.05$). The difference at T3 was significant ($P < 0.05$).

In summary, the height of *D. glomerata* in the mixed cultures and at both low and high clipping heights was lower than that of *L. multiflorum*, but in the monocultures the reverse was the case. The potential of *D. glomerata* to grow taller was not realized in the mixed culture. Between the T2 and T3 clipping interval, the difference in height between the two species decreased.

Effect of clipping on growth traits and competitive ability

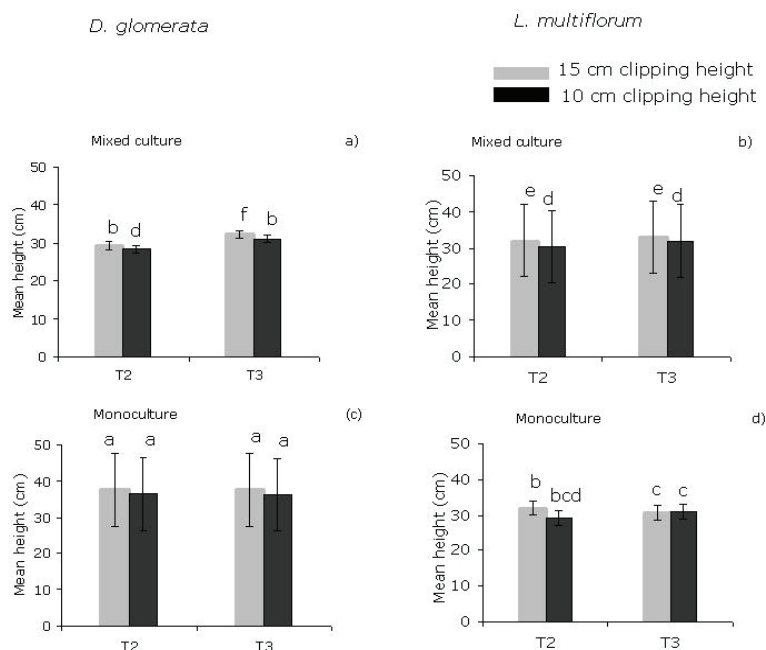


Figure 2.3 Mean height (cm) of *D. glomerata* and *L. multiflorum* in mixed cultures (a and b) and monocultures (c and d) clipped at low (15 cm height above the ground) and high clipping intensity (10 cm height) at T2:13 weeks after sowing and T3:18 weeks after sowing. Pairs that are labelled with different letters were found significantly different by the Scheffé *post hoc* test ($P \leq 0.05$). Vertical bars (whiskers) denote 0.95 confidence intervals

Table 2.2 Nested ANOVA results: effect on height of clipping time nested in clipping, culture and species

Effect	SS	DF	MS	F_{Observed}	P
Species	406	1	406	31.56	< 0.001
Culture	554	1	553.9	43.05	< 0.001
Clipping	107	1	106.8	8.3	< 0.01
Time	1271	12	105.9	8.23	< 0.001
(Species*Culture*Clipping)					
$F_{\text{Expected}}: F_{12, 264}=8.2334, P < 0.001$					

2.3.2 Effect of clipping and species on dry matter

Results from the nested ANOVA (Table 2.3) show significant differences in dry matter owing to the effects of the two species ($F_{12, 305} = 122.1$; $P < 0.001$), culture ($F_{12, 305} = 581.7$; $P < 0.001$), clipping height ($F_{12, 305} = 24.1$; $P < 0.001$), and time of clipping nested within these interactions ($F_{12, 305} = 24.1$; $P < 0.001$). Clipping height alone had no significant effect. Figure 2.4 shows the mean dry matter (g) for *D. glomerata* and *L. multiflorum* in mixed cultures and monocultures and clipping intensity at 15 cm height and 10 cm height above the ground. The letters on top of the bars indicate significance in the differences between treatment pairs according to the Scheffé *post hoc* test. The dry matter of *D. glomerata* monocultures clipped at low clipping height (15 cm) was higher in the mixed than in the monocultures and the difference was significant ($P < 0.05$). Unlike in the mixed cultures, the dry matter yield in monocultures of *D. glomerata* increased significantly ($P < 0.05$) between T2 and T3. On the other hand, at T2, when *L. multiflorum* was clipped at low rather than high clipping height, the dry matter yield was higher. The dry matter yield of *L. multiflorum* in mixed cultures increased significantly at T3, particularly at 10 cm (high clipping intensity) ($P < 0.05$). This was significantly higher than for *D. glomerata* ($P < 0.05$) at the same 10 cm clipping height, where the dry matter yield increased by only 0.09 g (Table 2.1).

Therefore, in both species dry matter yield in the mixed cultures was lower under low clipping intensity (15 cm) than under high clipping intensity (10 cm) but the reverse was true for monocultures. In monocultures, the dry matter yield of *D. glomerata* was higher but in mixed cultures it was lower than height.

Effect of clipping on growth traits and competitive ability

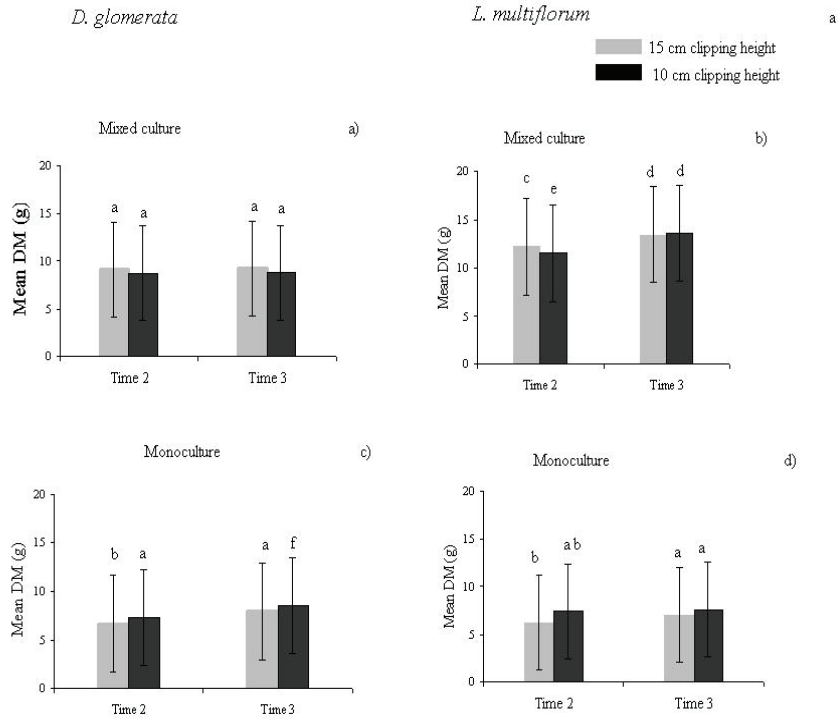


Figure 2.4 Mean DM of *D. glomerata* and *L. multiflorum* in mixed cultures (a and b) and monocultures (c and d) under low clipping intensity (15 cm clipping height above the ground) and high (10 cm clipping height), at T2:13 weeks after sowing and T3:18 weeks after sowing. Pairs that are labelled with different letters on top of the bars were found significantly different according to the Scheffé *post hoc* test ($P \leq 0.05$). Vertical bars (whiskers) denote 0.95 confidence intervals.

Table 2.3 Nested ANOVA results: effect of time nested in clipping, culture and species on dry matter

Effect	SS	DF	MS	F _{Observed}	P
Species	194.5	1	194.5	122.1	< 0.001
Culture	926.8	1	926.8	581.7	< 0.001
Clipping	3.5	1	3.5	2.2	> 0.1
Time(Species*Culture*Clipping)	460	12	38.3	24.1	< 0.001
<i>F_{expected}: F_{12, 305}=24.058, p < 0.001</i>					

2.3.3 Height and dry matter yield vs. relative regrowth rate

L. multiflorum increased more in dry matter yield and regrowth rate than did *D. glomerata*. (Table 2.4, Figure 2.5). Table 2.4 shows an increase in regrowth of the height and dry matter yield of *D. glomerata* and *L. multiflorum* and their relative regrowth rate. The Table 2.1 data were used to compute the regrowth and relative regrowth rate. In monocultures the height of *D. glomerata* clipped at low (15 cm) height increased, whereas that of *L. multiflorum* decreased. Dry matter yield increased in *D. glomerata* by 1.25 g. This was higher than the increase of 0.78 g in *L. multiflorum*. The higher increase in height and dry matter yield of *D. glomerata* was consistent with the higher relative regrowth rate of 0.017 gw^{-1} (RRR of *L. multiflorum*: 0.012 gw^{-1}). In the monocultures clipped at high intensity (10 cm height), however, the height of *D. glomerata* decreased by 0.25 cm, whereas that of *L. multiflorum* increased by 1.75 cm. The increase in dry matter yield of *D. glomerata* (1.19 g) was higher than that of *L. multiflorum* (0.17), and this was consistent with the relative regrowth rate, which was higher for *D. glomerata* (0.015 gw^{-1}) than for *L. multiflorum* (0.007 gw^{-1}).

In mixed cultures, *D. glomerata* clipped at low clipping height increased in height by 2.88 cm, whereas *L. multiflorum* increased by only 1.09 cm. As regards dry matter yield, the positions were reversed, with *D. glomerata* increasing by only 0.07 g and *L. multiflorum* increasing by 1.28 g. *L. multiflorum* showed a higher relative regrowth rate (0.020 gw^{-1}) than *D. glomerata* (0.001 gw^{-1}). In mixed cultures under higher clipping height, *D. glomerata* increased in height by 2.68 cm, which was almost twice that achieved by *L. multiflorum* (1.49 cm). Under low clipping height, the reverse was true as regards dry matter yield. The dry matter yield of *L. multiflorum* (2.12 g) increased more than that of *D. glomerata* (0.09 g). The relative regrowth rate for *L. multiflorum* (0.003 gw^{-1}) was higher than that for *D. glomerata* (0.001 gw^{-1}). The results of the *t*-test (tabulation not shown) showed that the regrowth of *L. multiflorum* was significantly higher than that of *D. glomerata* ($P < 0.05$).

Clipping had greater effect on height than on dry matter yield but the increase in dry matter yield was more consistent with relative regrowth rate. Figure 2.5 shows a strong positive linear relationship for relative regrowth rate versus regrowth in dry matter (RRR = $0.0008 + 0.0143 * x$ ($p < 0.05$, $r^2 = 0.96$). The increase in relative regrowth rate with dry matter yield was not evident in height. *L. multiflorum* was therefore considered to have higher competitive

ability because it showed a higher increase in the dry matter yield of the mixed cultures and a more positive relationship with relative regrowth rate.

Table 2.4 Mean regrowth in height (cm), DM (g), and relative regrowth rate (g week⁻¹) of *D. glomerata* (Dt) and *L. multiflorum* (L) in monocultures and mixed cultures under low and high clipping intensities. The mean height and DM regrowth are obtained from Table 2.1, section 2.2.4.

Species	Culture	Clipping Height (cm)	Mean height regrowth (cm)	Mean DM regrowth (g)	RRR (g week ⁻¹)
Dt	Mono	15	1.16	1.25	0.017
Dt	Mono	10	- 0.25	1.19	0.015
Dt	Mix	15	2.88	0.07	0.001
Dt	Mix	10	2.68	0.09	0.001
L	Mono	15	- 1.31	0.78	0.012
L	Mono	10	1.75	0.77	0.007
L	Mix	15	1.09	1.28	0.020
L	Mix	10	1.49	2.12	0.033

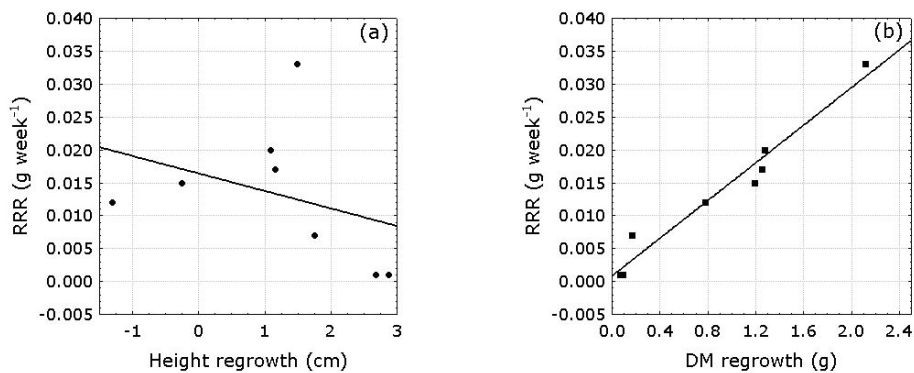


Figure 2.5 Relationship between (a) regrowth in height (cm) with RRR (g week⁻¹) and (b) regrowth in DM with RRR (g week⁻¹). A strong positive linear relationship is shown for RRR versus regrowth in DM: $RRR = 0.0008 + 0.0143 * x$ ($p < 0.05$, $r^2 = 0.96$).

2.4 Discussion

A strong positive linear relationship between relative regrowth rate and regrowth in dry matter was shown, but not with height (Figure 2.5). These results are comparable to those in the studies carried out by Navas and Moreau-Richard (2005), who found no relationship between species competitive response and height. The results are also comparable to the findings by Burboa-Cabrera *et al.* (2003) on grazing intensity and tiller height. Although the potential of *D. glomerata* to grow taller was not realized in the mixed cultures, the increase in dry matter yield enabled a higher competitive ability, whereas *L. multiflorum*, which is believed to grow larger and germinated two weeks earlier, did not show this trait in monocultures.

The advantage of early germination and establishment in *L. multiflorum* was in agreement with Humphrey and Schupp (2004) and with Kuijper *et al.* (2004) that early emergents usually become taller and more competitive (Tilman, 1988). This notion would not hold entirely for this study, since, rather than the increase in grass height, increase in dry matter yield was the dominant trait. As seen before, plant weight and size have also been related to competitive ability (Damgaard, 1999; Fetene, 2003; Riba, 1998; etc.). The results confirm this and suggest that the early establishment, larger stature and higher dry matter yield of *L. multiflorum* contributed to its higher relative regrowth rate and higher competitive ability in the mixed cultures. This is in conformity with the notion that competition depends largely on growth rate, which is a product of dry weight (Tilman, 1988).

The link between the response to competition and plant size is not, however, universal (Navas and Moreau-Richard, 2005) and has not, to the knowledge of the authors, been investigated in monocultures. In this study, the increase in dry matter yield was not significantly affected by clipping unless in interaction with culture and species. The results suggest that, more than grazing intensity, culture and species may influence the competitive ability of *D. glomerata* and *L. multiflorum*.

The greater significance of dry matter yield over plant height in the competitive interactions was found for *L. multiflorum* in mixed cultures. In mixed cultures clipped at low intensity (15 cm), positions were reversed for the species. *L. multiflorum* showed higher regrowth under both low and high clipping intensities (Table 2.4). Furthermore, the results of the *t*-test showed that the regrowth of *L. multiflorum* was significantly higher than that of *D. glomerata* ($P < 0.05$). The

higher dry matter yield and relative regrowth rate of *L. multiflorum* in mixed cultures suggests that it has a higher competitive ability.

D. glomerata was found to have higher dry matter yield in the monocultures. The findings suggest that *D. glomerata* has the potential to out-compete *L. multiflorum*. Moreover, *L. multiflorum*, being an annual species already showed signs of senescence by the end of the experiment while *D. glomerata* was still growing. This suggests that the dominance of the former species may be reversible later in the growing season. However, the scope of this research did not cover such an investigation.

It has been shown that, in the absence of *L. multiflorum*, *D. glomerata* becomes more productive over time, whereas the contrary is true when the two are mixed. In the mixed cultures, *L. multiflorum* showed higher dry matter yield and relative regrowth rate and therefore a higher positive response to inter-specific competition than to intra-specific competition. The results suggest that defoliation pressure on *L. multiflorum* is more detrimental if the species is occurring in monocultures than if it is co-occurring with *D. glomerata*.

Both species showed higher regrowth in mixed cultures than in monocultures. This may be because the species have a positive effect on each other, with *L. multiflorum* showing higher competitive ability. Rodriguez and Brown (1998) found comparable results in *P. annua*, which showed significantly greater biomass in mixed stands than in monocultures. Similar results are reported by Flower and Rausher (1985). In their study on the performance of single versus mixed plant species, Kuijper *et al.* (2004) found that at the lowest nitrogen level the performance of two species decreased when grown together rather than in monocultures.

Regrowth was higher under high clipping intensity (10 cm) than under low intensity (15 cm). Relative regrowth rate was also higher in the mixed cultures clipped at high intensity than in those clipped at lower intensity (Table 2.4, Figure 2.4). This shows a positive effect of higher defoliation intensity on the growth of the two species. Other studies have found that some plants benefit from defoliation damage by grazing through overcompensation (e.g., Riba, 1998), although other studies (e.g., Lucas *et al.*, 2004) have not found this effect. In another study, longer lax grazing has led to increased tiller density and herbage production (Garay *et al.*, 1997). Grasses are well adapted to being grazed or cut if, before the flowering stage is reached, leaf formation continues during and after subsequent defoliation (Langer, 1979). During the vegetative phase, the

meristematic zones are usually located close to the soil surface beyond the reach of animals and cutting machines. Even if some meristems are removed by defoliation, they may readily be replaced by the appearance of new tillers (Langer, 1979). The duration of this experiment was limited to the vegetative stage of growth in both species. This may be a reason why higher clipping did not have the expected higher detrimental effect.

Therefore, the two species seem to attain higher productivity when mixed and clipped at higher intensity (10 cm above the ground) than when growing separately and clipped at lower intensity (15 cm). Further research should investigate clipping height and species mix for guiding stocking density and hay cutting at field level.

Relative regrowth rate could also have been affected by the traits and other factors not investigated in this study. There are numerous traits that may be considered including emergency and establishment, tiller and leaf appearance rate, leaf area expansion rate, plant longevity, defence investment (Goldeberg, 1996; Navas and Moreau-Richard, 2005; Kuijper *et al.*, 2004; Damgaard, 1999; Espigares *et al.*, 2004). Although such traits affect shoot regrowth, equally important are the environmental factors (Dayan *et al.*, 1981; Vesik and Westoby, 2001).

Some factors have direct interaction with the traits, for example, light interception (de Wit, 1965; Johnson *et al.*, 1983; Tilman 1988), substrate size and nitrogen use efficiency (Loo, 1993), and temperature (e.g., de Wit, 1978; Hardegree and Van Vector 1999; Loo, 1993). Dayan *et al.* (1981) argue that an accurate prediction of the growth of grasses under defoliation should include the number, size, and phenological state of the tillers present at the moment of cutting, the current level of carbohydrate reserves, and the residual green leaf area. Loo (1993) includes cutting frequency, while others (e.g., Garay *et al.*, 1997; Hitchmough *et al.*, 2004) add seeding rate, timing and duration of grazing. However, insight is gained by taking a simple perspective and exploring the implications of a few factors, with other potentially important factors "held constant" for the sake of ease of analysis (Tilman, 1988).

In this study, we demonstrate that traits which determine competitive ability in the early established stage of the studied forage grass species can be identified through a short-term experiment. Such experiments reasonably explore vegetation growth processes that would require long-term empirical studies (e.g., Johnson *et al.*, 1983). This means that competitive ability of the various co-occurring forage species in the early established stage of growth may be more

efficiently established. Whether the species that have initial relatively higher yields eventually replace the other species, however requires further research.

2.5 Conclusions

This research has established that clipping has a more significant effect on height than on dry matter yield, and that increase in dry matter yield determines the relative regrowth rate in the species. Our results are in conformity with the notion that competition depends largely on growth rate.

A dominant growth characteristic (dry matter yield) can be identified during the early establishment stages of *D. glomerata* and *L. multiflorum* when the two are grown in monocultures and mixed cultures under variable grazing intensity. *L. multiflorum* attained higher dry matter yield, consistent with higher regrowth and regrowth rate and therefore higher competitive ability. Therefore, traits that determine competitive ability can be identified in such a short-term experiment. Further investigation is needed to establish if the dominance of the trait to increase in dry matter yield and the competitive ability of *L. multiflorum* may be sustained beyond the current experiment time.

The two species may be more productive when mixed and clipped at high intensity (10 cm above the ground) than when growing separately and clipped at lower intensity. This needs to be investigated further considering optimal clipping height and species mix for guiding stocking density and hay cutting at field level.

At field level, selective grazing may reduce the competitive ability of preferred forage species if the suppression of their regrowth by higher grazing intensity is greater than that in co-occurring less preferred ones. This leads to vulnerability of preferred forage species. Using the same experiment set up, the regrowth capacity of the two species under selective clipping is, therefore, investigated in the next chapter.



CHAPTER 3

Effect of selective clipping on regrowth and competitive ability of forage grass

Based on: Jane Bemigisha, Sip E. van Wieren, Andrew K. Skidmore, Alfred Stein, Jasper van Ruiven and Jan de Leeuw. (In preparation). Contrasting regrowth and competitive ability of *Lolium multiflorum* and *Dactylis glomerata* under selective clipping

Abstract

Regrowth capacity is one of the attributes that affect the competitive ability and persistence of forage plant species but this has not been established for most co-occurring livestock forage species under selective grazing. In a greenhouse experiment, we investigated the regrowth and competitive ability of a preferred and less preferred grass species, *Lolium multiflorum*, and *Dactylis glomerata*, respectively. We tested the effects of clipping intensity and species culture (monoculture and mixed) on the regrowth of the two species, and whether selective clipping (simulating selective grazing) affected *D. glomerata* more when clipped at less intensity than *L. multiflorum*. Regrowth in monoculture was significantly higher for *D. glomerata* than for *L. multiflorum* ($P < 0.05$). Mixed culture comparisons showed similar differences, but mean regrowth of *L. multiflorum* was significantly higher than that of *D. glomerata* ($P < 0.001$), suggesting that it was negatively affected by the presence of *L. multiflorum*. Selective clipping did not lead to higher competitive ability in *D. glomerata* as expected. Its neighbour *L. multiflorum* showed higher regrowth under selective clipping, possibly because of its head-start germination and larger stature. This may change over time because the mean regrowth of *D. glomerata* was greater under selective clipping than under uniform clipping (although the difference was not statistically significant). Selective grazing may therefore shift the regrowth and competitive ability in favour of *D. glomerata*.

3.1 Introduction

The vulnerability of plant species preferred for livestock grazing calls for prediction of their performance and survival in mixed vegetation communities (Noy-Meir, 1990). The performance of such species depends on management such as sowing time (e.g., Fetene, 2003) and traits, such as germination time and plant size (Humphrey and Schupp, 2004). The effect of selective herbivory may also depend on interactions of various environmental factors and this makes it difficult to predict. Although competition in forage species (e.g., Prins and Nell, 1990; Olf *et al.*, 1999; Arsenault and Owen-Smith, 2002; Humphrey and Schupp, 2004) and plant responses to grazing in mixed plant species (e.g., Berendse *et al.*, 1992; Loo, 1993; Kuijper *et al.*, 2004; Seggara *et al.*, 2005; Tilman, 1988) have been widely studied, the simultaneous effects of selective grazing and competition for most co-occurring forage species is not known (Lenssen *et al.*, 2004).

Competitive abilities have been studied in various ways, leading to different predictions and interpretations (Golderberg 1996). Golderberg (1990) defined competitive ability in terms of either the competitive effect (ability of an individual to suppress other individuals), or on the competitive response (referring to the ability of an individual to avoid being suppressed and ability to acquire and use resources). Competitive abilities may also be based on differences in growth rates, rate of increase in height and access to nutrients (Tilman, 1988). Competitive ability of forage plant species in response to defoliation may be determined by the regrowth capacity, i.e., renewed growth of leaves, the expansion of new shoots (Grime, 1979), and shoot density (e.g., Lenssen *et al.*, 2004). Based on these definitions, this research has determined competitive ability through regrowth capacity based on dry matter (g) of re-sprouted plant tissue clipped or removed between clipping intervals.

The objective of this study was to investigate the effect of selective clipping (simulating selective grazing) on the regrowth and competitive ability of *L. multiflorum* when mixed with a species less preferred by livestock grazers, *D. glomerata*. We tested the effect of selective clipping (clipping *D. glomerata* at a higher clipping height than *L. multiflorum*). *D. glomerata* was expected to have higher regrowth under selective clipping than under uniform clipping as a consequence of *L. multiflorum* being clipped at a higher intensity while in the mixed cultures.

3.2 Methods

3.2.1 Study species

Two forage grass species, *L. multiflorum* and *D. glomerata*, with different growth characteristics and differing in terms of preference by livestock grazers, were selected. A detailed description of their characteristics is given in section 2.2.1. Although identified in Majella National Park, Italy, a Mediterranean field study site of the wider research connected to this study, the species also appear together elsewhere (temperate, tropical and subtropical areas) in natural or cultivated pastures (Hannaway *et al.*, 1999; Hubbard, 1968; Avery *et al.*, 2000; Lowe *et al.*, 2005). In this study, *L. multiflorum* was identified as being preferred to *D. glomerata* by grazers, although the preference may differ depending on different field situations. Both species are widely grown for pasture and hay. Their regrowth and competitive ability under selective grazing, like those of most co-occurring livestock forage species, are not adequately studied.

3.2.2 Experimental set-up, clipping treatments and measurements

The same experiment set-up and clipping design as in section 2.2.2 was used, but the clipping treatments for this study differed by including selective clipping. In this study clipping intensity was classified into (a) uniform clipping, that is, clipping at the same height above the ground) and (b) selective clipping, that is, clipping *L. multiflorum* at high intensity (5 cm) to emulate its being preferred by grazers while *D. glomerata* was clipped at a lower intensity (10 cm). To minimize experimental time and space, the replicates of *D. glomerata* designed for clipping at high intensity were clipped instead at medium intensity (10 cm) to cater for selective clipping. This means that for *D. glomerata* the clipping intensity class code of High (5 cm) was replaced by another Medium class code (10 cm). Consequently, the analysis and sections on selective clipping show two medium clipping treatments of *D. glomerata* at Medium (S) and Medium (U), representing selective and uniform clipping, respectively. Note that the medium clipping intensity in both uniform and selective clipping was the same (10 cm); the codes (S and U) are used only for identification purposes. The clipped plant material was dried as in section 2.3.3. Regrowth was calculated as the difference between the dry matter of the clipped material at clipping T2 and the dry matter at clipping T3. Prior to analysis, regrowth of monocultures (sown with 40 seeds) was divided by two to enable comparison with the mixed

cultures (20 seeds for each of the two species). Data on dry matter yield is contained in Table 3.3.

3.2.3 Analysis

The analysis was conducted in two parts: (a) to test the effects of uniform clipping intensity, culture (monocultures and mixed) and species on regrowth, and (b) to test the effect of selective clipping (clipping *D. glomerata* at lower intensity than *L. multiflorum*).

3.2.3.1 Testing the effect of uniform clipping on regrowth

For this part of the analysis, Low (15 cm) and Medium (10 cm) clipping intensity replicates were used. Table 3.1 shows the species, cultures and clipping combinations.

Table 3.1 Data structure for uniform clipping analysis. Clipping intensity: Low = 15 cm height; Medium = 10 cm height. Note that the *high clipping* intensity for *D. glomerata* are not included because the replicates were clipped instead at medium height to test the effect of selective clipping.

<i>Species</i>	<i>Culture</i>	<i>Clipping height</i>	<i>No. of samples</i>
<i>L. multiflorum</i>	Monoculture	Low	18
		Medium	18
	Mix	Low	18
		Medium	18
<i>D. glomerata</i>	Monoculture	Low	18
		Medium	18
	Mix	Low	18
		Medium	18
Total			144

A nested ANOVA was used to test the effect of clipping intensity nested within the species and species culture interaction, as illustrated in Figure 3.1.

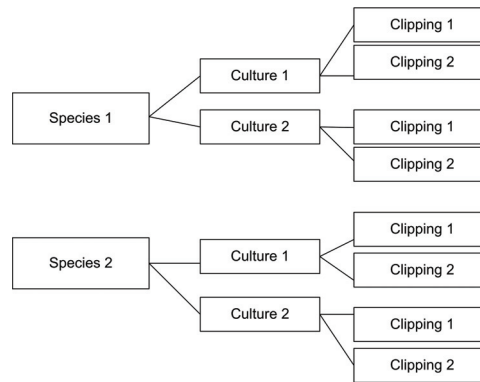


Figure 3.1 Illustration of the nested ANOVA model: clipping intensity nested in culture and species. Species 1 = *D. glomerata*, Species 2 = *L. multiflorum*; Culture 1 = monoculture, Culture 2 = mixed culture; Clipping 1 = low clipping intensity, Clipping 2 = high clipping intensity.

The following model was used:

$$\text{Regrowth} = (\text{Species} * \text{Culture}) / \text{Clipping}$$

Indicating that the clipping effect is nested within the full factorial species \times culture interaction model. This model is equivalent to the following formula:

$$\text{Regrowth}_{ijkl} = (\text{Species}_i * \text{Culture}_j) / \text{Clipping}_k + e_{ijkl} \quad (\text{Eq.3.1})$$

where:

- Species_i = *D. glomerata* (i = 1) and *L. multiflorum* (i = 2)
- Culture_j = type of stand, i.e., mono (j = 1) and mixed (j = 2)
- Clipping_k = clipping intensity, i.e., low (k = 1) and medium (k = 2)
- Regrowth_{ijkl} = the mean response for treatment combination i, j and k
- e_{ijkl} = a normally distributed error term with mean zero.

3.2.3.2 Testing the effect of selective clipping on regrowth

Selective clipping was done by clipping *L. multiflorum* at high intensity (5 cm) and *D. glomerata* at lower intensity (10 cm) to emulate the higher preference by grazers for the former. Table 3.2 shows the species, cultures and clipping combinations. We expected that the mean regrowth of *D. glomerata* under uniform clipping would be less than under selective clipping, because under selective clipping the competitive effects of its neighbour *L. multiflorum* would be suppressed by the higher clipping intensity.

To test whether regrowth of *D. glomerata* was significantly affected by selective clipping (i.e., when clipped at a lower intensity than *L.*

multiflorum), the mean regrowth under selective clipping (coded S) was compared with mean regrowth under uniform clipping (coded U). An independent samples *t*-test was used for the comparison. The hypothesis tested was:

$$H_0: \mu_{Dt_U} = \mu_{Dt_S}$$

$$H_a: \mu_{Dt_U} \neq \mu_{Dt_S}$$

where μ_{Dt_U} and μ_{Dt_S} are the regrowth means of *D. glomerata* under uniform clipping and selective clipping, respectively.

For both the ANOVA and the *t*-test, the effect was considered significant at $P \leq 0.05$.

Table 3.2 Data structure for testing the effect of selective clipping. Clipping intensity treatments: High = 5 cm clipping height, Medium = 10 cm clipping height, (S) = selective clipping, (U) = uniform clipping.

Species	Culture	Clipping intensity	No. of samples
<i>L. multiflorum</i>	Mix	High	18
		Medium	18
<i>D. glomerata</i>	Mix	Medium (S)	18
		Medium (U)	18
Total			72

3.3 Results

3.3.1 Effect of clipping intensity, culture and species on regrowth (uniform clipping)

A contrasting response to culture treatments was found within and between the regrowth of the two species, and we found that *D. glomerata* was negatively affected by the presence of its neighbour *L. multiflorum*. Table 3.3 shows that the total mean regrowth in the monocultures of *D. glomerata* was 2.28 g greater than in the mixed cultures. On the other hand, regrowth in the monocultures of *L. multiflorum* was half that in the mixed cultures. Statistical comparison of the two species (Table 3.3 and 3.4) shows that the total mean regrowth in the monocultures of *D. glomerata* (2.44 g) was significantly higher than in the monoculture of *L. multiflorum* (1.55 g), and the difference was highly significant ($P < 0.001$). In the mixed cultures, the mean regrowth of *L. multiflorum* was significantly higher than that of *D. glomerata* ($P < 0.001$). Therefore, if the culture was a monoculture, we had higher regrowth of *D. glomerata*; if the culture

was mixed, we had higher regrowth of *L. multiflorum* (Table 3.5). This shows that the regrowth of *D. glomerata* was negatively affected by the presence of its neighbour *L. multiflorum*.

Table 3.3 Mean dry matter (DM g) at T2: after 13 weeks and T3: after 18 weeks and mean regrowth (DM g) of *D. glomerata* (Dt) and *L. multiflorum* (L) in monocultures and mixed cultures at clipping intensities: Low (15 cm above the ground) and Medium (10 cm above the ground). Regrowth figures for monocultures are divided by two. Standard errors of the means and the 95% confidence intervals are presented in Table 2.1

Species	Culture	Clipping	Mean dry matter	Mean dry matter	Mean regrowth (DM g)
			(DM g) T2	(DM g) T3	
<i>Dt</i>	Mix	Low	9.09	9.16	0.07
<i>Dt</i>	Mix	Medium	8.67	8.76	0.09
<i>Dt</i>	Mono	Low	6.66	7.91	1.25
<i>Dt</i>	Mono	Medium	7.11	8.51	1.19
<i>L</i>	Mix	Low	12.2	13.45	1.28
<i>L</i>	Mix	Medium	11.5	13.62	2.12
<i>L</i>	Mono	Low	6.21	6.98	0.78
<i>L</i>	Mono	Medium	7.37	9.16	0.77

Table 3.4 Results of nested ANOVA for clipping nested within species and culture. Species: *L. multiflorum*, *D. glomerata*; clipping: Low and Medium clipping intensities.

Treatment	Estimate	Std. Error	t-value	P
Species	1.99	0.43	4.58	< 0.001
Culture	1.69	0.43	3.89	< 0.001
(Species * culture)/ clipping	-2.64	0.62	-4.26	< 0.001

Table 3.5 Regrowth as response to species, culture and clipping intensity in uniform clipping. *Dt* = *D. glomerata*, *L* = *L. multiflorum*.

Species	Culture	Clipping intensity	Response within species	Response between species
<i>Dt</i>	Monoculture	Low	-	<i>Dt</i> > <i>L</i>
<i>Dt</i>	Monoculture	Medium	Medium < Low	<i>Dt</i> > <i>L</i>
<i>Dt</i>	Mixed	Low	-	<i>Dt</i> < <i>L</i>
<i>Dt</i>	Mixed	Medium	Medium > Low	<i>Dt</i> < <i>L</i>
<i>L</i>	Monoculture	Low	-	<i>L</i> < <i>Dt</i>
<i>L</i>	Monoculture	Medium	Medium < Low	<i>L</i> < <i>Dt</i>
<i>L</i>	Mixed	Low	-	<i>L</i> > <i>Dt</i>
<i>L</i>	Mixed	Medium	Medium > Low	<i>L</i> > <i>Dt</i>

3.3.2 Effect of selective clipping

Selective clipping increased the regrowth of *D. glomerata*, but this was not significant. Figure 3.2b show the mean regrowth (DM g) of *D. glomerata* under selective clipping (M-selective) and uniform clipping (U-selective). Figure 3.2a shows regrowth (DM g) of *L. multiflorum* under (high) selective clipping (H-selective). The regrowth of *D. glomerata* was higher under selective clipping (0.75 g) than under uniform clipping (0.09 g). This difference is rather large, but the *t*-test results showed no statistical significance. We thus failed to reject the null hypothesis and concluded that selective clipping did not lead to significantly higher regrowth and therefore higher competitive ability of *D. glomerata*. Under selective clipping, *D. glomerata* was expected to have higher regrowth than *L. multiflorum*, as a consequence of *L. multiflorum* being clipped at a higher intensity. However, the mean regrowth was still less than that of *L. multiflorum* (Figure 3.2a).

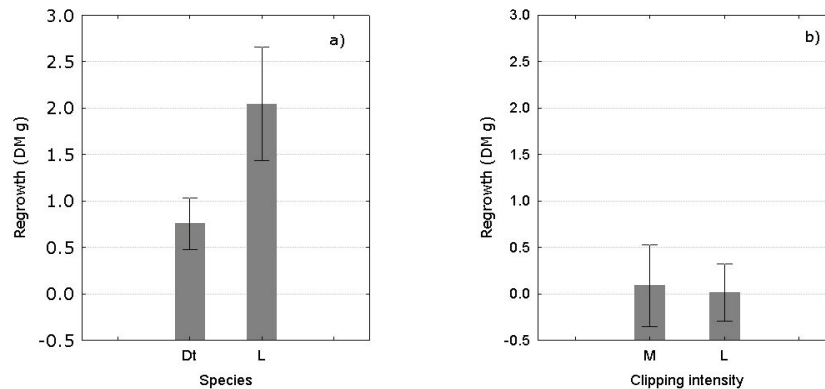


Figure 3.2 Mean regrowth of (a) *D. glomerata* (Dt) and *L. multiflorum* (L) under selective clipping, and (b) *D. glomerata* clipped at medium height in mixed cultures of selective treatment (M-selective) and uniform treatment (M-uniform). Vertical bars (whiskers) denote 0.95 confidence intervals.

3.4 Discussion

Under uniform clipping, we found contrasting responses in the regrowth of the two species to clipping intensity and culture, but in mixed cultures both species showed higher regrowth when clipped at the higher clipping intensity (10 cm) than at the lower intensity (15 cm). The higher regrowth in the mixed species under higher clipping intensity demonstrates high competitive traits in both grass species. Such grasses rapidly regrow in response to intense damage and thus

have the capacity to rapidly re-establish leaf canopy following defoliation (Grime, 1979). Other plants, such as *Lolium perenne*, increase photosynthetic efficiency as compensation following defoliation (Wolfson, 1999). In their experiment, Boyd and Svejcar (2004) also found that production values were higher for clipped plots than for unclipped plots, indicating compensatory production of the studied herbaceous plants in response to defoliation. Minimal changes in pasture species composition have also been found as a result of varying grazing management through seasonal rests, mob stocking and cutting for hay (Garden *et al.*, 2000). Our results suggest higher productivity under intensive grazing. This response is, however, not uniform among species in monocultures. For example, the regrowth in monocultures of *D. glomerata* was higher under low clipping intensity than under medium, and higher than found in *L. multiflorum*. The response to culture treatments in the regrowth of the two species showed that *D. glomerata* was negatively affected by the presence of its neighbour *L. multiflorum*. If the culture was a monoculture, then we had higher regrowth of *D. glomerata*; if the culture was mixed, then we had higher regrowth of *L. multiflorum*. This phenomenon has also been found in *L. multiflorum* when mixed with other species (Lowe *et al.*, 2005). Navas and Moreau-Richard (2005) have found that the abundance of target species depends on the competitive response of neighbour species. Comparable results have been found by Seggara *et al.* (2005), in which competitive *Elyonurus adustus*, *Leptocryphium lanatum* and *Andropogon semiberbis* show highly significant levels of neighbourhood interference.

In this study, we found that the total regrowth of *D. glomerata* was higher in monocultures than in mixed cultures, but the total regrowth of *L. multiflorum* was less in monocultures than in mixed cultures. The results suggest that, in contrast to *L. multiflorum*, under uniform grazing *D. glomerata* regrows more when in monocultures than in mixtures. Therefore, in pasture management practices that include *L. multiflorum*, consideration may be given to a mixed culture rather than a monoculture in order to increase forage productivity. This requires further testing of the response, using different species mixes.

Contrary to expectation, selective clipping did not lead to higher competitive ability of *D. glomerata*. As in uniformly clipped mixed cultures, the regrowth of *L. multiflorum* was higher than that of *D. glomerata* under selective clipping. Comparable results were shown by Lenssen *et al.* (2004), in which the responses of *Archanara*-infested and non-infested *Phragmites* shoots revealed no increased competitive suppression by *Epilobium* due to selective herbivory. Their study suggests that, rather than selective grazing, different

environmental interactions may have determined the competitive abilities. In our study, *L. multiflorum* may owe its higher competitive ability to such traits as earlier germination and larger stature. Humphrey and Schupp (2004) have found that *B. tectorum* has a competitive advantage because of a head-start over native perennial grass seedlings. Espigares *et al.* (2004) have found that early emergence of *Retama sphaerocapus* seedlings increases their biomass in relation to herbaceous plants. Fetene (2003) has also found comparable results in *Acacia etbaica* and *Hyperrenia hirta*, where *Hyperrenia* competes more aggressively with *Acacia* when the latter is planted within an already grown grass community. In addition, the large stature (larger basal area) of *L. multiflorum* enhances its regrowth in relation to *D. glomerata*. The advantage of basal area in plant competition has been attested by Navas and Moreau-Richard (2005). In addition, defoliation prior to heading has been reported to foster regrowth in *L. multiflorum* (Hannaway *et al.*, 1999).

Under continued selective clipping, the higher regrowth of *L. multiflorum* may be reversible at a time beyond the experiment. The reason is that *D. glomerata* showed a higher regrowth under selective clipping (in which *L. multiflorum* was clipped at higher intensity) than under uniform clipping, although the statistical difference was not significant. The observed response of *D. glomerata* under selective clipping is not conclusive given the insignificant statistical difference, apart from other clues. To reiterate, *D. glomerata* is a perennial grass, with higher regrowth in the monoculture; it grows taller, has a deeper root system, and continues to grow later in the season than the annual *L. multiflorum*. *D. glomerata* has also shown exceptional adaptation to defoliation because of its high sheath: stem ratio, which, it is proposed, allows it to maintain photosynthesis and a level of carbon supply sufficient to support regrowth (Cullen *et al.*, 2006). These traits suggest potential for higher competitive ability beyond the experiment time (i.e., at the time when *L. multiflorum*, an annual grass, gets to the senescence stage). Unlike *D. glomerata*, *L. multiflorum* already showed signs of senescence by the end of the experiment. Lack of comparable replicates for *L. multiflorum* under selective clipping, however, limited further understanding of its response.

To sum up, a statistically based greenhouse experiment provided important and unexpected information on regrowth for different species in relation to different clipping intensities. Clipping has been used to simulate selective livestock grazing. The method may be applied to different species mixes at field level, considering the role of

underlying competition mechanisms such as resource and tiller development dynamics, clipping frequency, the manner of forage removal, trampling, dunging and resting (Bakker, 1989; Loo, 1993; Tilman, 1988).

3.5 Conclusions

Under uniform clipping, we found contrasting response to clipping intensity and culture treatments in the regrowth of the species. In monocultures, both species showed a more positive response to higher clipping intensity, suggesting higher productivity under intensive uniform grazing. The statistical results, however, showed that under uniform clipping rather than clipping intensity the higher regrowth of *L. multiflorum* compared with that of *D. glomerata* was largely attributable to species and culture.

The response to culture treatments within and between the regrowth of the two species showed that *D. glomerata* was negatively affected by the presence of its neighbour *L. multiflorum*. Comparing the two species under uniform clipping, the total mean regrowth in monocultures of *D. glomerata* was significantly higher than that in monocultures of *L. multiflorum* ($P < 0.05$). Mixed culture comparisons showed similar differences, but mean regrowth of *L. multiflorum* was significantly higher than that of *D. glomerata* ($P < 0.001$).

Selective clipping did not lead to higher competitive ability of *D. glomerata* as expected. The regrowth of *L. multiflorum* was higher than that of *D. glomerata*, possibly because former germinated two weeks earlier. Over time, however, selective clipping can shift regrowth and competitive ability in favour of *D. glomerata*. *D. glomerata* showed higher regrowth in response to selective rather than uniform clipping, although the statistical difference was not significant. Moreover, perennial nature may give it an advantage over the annual *L. multiflorum* late in the growing season. This needs to be further investigated. Underlying competition mechanisms such as resource and tiller development dynamics as well as clipping frequency which were controlled or not included in this study may also be important considerations for further research.

The application of this study to different species mixes, especially in field situations, will provide an opportunity to confirm the findings. At field level, the research effort needed to study the competitive dynamics in various co-occurring forage species and covering large areas may be costly. Remote sensing approaches that improve information detail, content and frequency of observation need to be

investigated. In the next chapter, we show that hyperspectral remote sensing can be used to study competitive ability of co-occurring forage grass based on associated biophysical vegetation variables such as dry matter yield and height.



CHAPTER 4

Hyperspectral remote sensing of defoliation intensity and competitive ability of forage grass

Based on: Jane Bemigisha, Andrew K. Skidmore, Alfred Stein, Herbert H.T. Prins, Sip van Wieren, Moses Azong Cho, Istiak Sobhan and Martin Schlerf (In review, IJRS). Hyperspectral features respond to defoliation and inter-specific grass competition.

Abstract

In a greenhouse experiment, we investigated changes in the response of narrow-band spectral reflectance, spectral indices and the red-edge position for two livestock forage grass species, *Dactylis glomerata* and *Lolium multiflorum*. The species were grown in mixed or monocultures and clipped at different intensities. Using a field portable spectroradiometer, canopy spectral measurements were taken before each clipping at the 13th and 18th week after sowing, referred to as T2 and T3 respectively. Analysis of Variance (ANOVA) showed that at T2, the effect of species cultures on spectral reflectance was significant ($P < 0.05$) in the visible (red) region, whereas the effect of clipping was significant ($P < 0.001$) only in the Near Infrared (NIR). At T3, the clipping effect covered bands, both in the visible and the NIR. This suggests that at T2 the effect of species culture on pigments and physiological condition dominated, while at T3 the clipping effect on the canopy became dominant. Changes in the response of the Physiological Reflectance Index (PRI), the Carter index, R_{694} , the ratio of the Transformed Chlorophyll Absorption in Reflectance Index to Optimized Soil-Adjusted Vegetation Index (TCARI/OSAVI) and the red-edge position showed potential for studying the effects of defoliation intensity and to show competitive ability in the forage species. The highest average percentage change in the index values ($\approx 75\%$ increase between T2 and T3) was observed in the PRI ($p < 0.0001$). The PRI was also associated with average height and dry matter yield of the species, growth variables that are associated with defoliation intensity and competitive ability. Therefore, the PRI may be the optimal index to further study defoliation intensity and competitive ability in forage species using reflectance data.

4.1 Introduction

Monitoring the effect of defoliation and competitive interactions among forage species on the growth and yield of grass species is important for pasture production and conservation (Dovrat *et al.*, 1980; Johnson *et al.*, 1983; Noy-Meir and Briske, 2002; Schut *et al.*, 2006). Better understanding is needed of the competitive ability of grazing-sensitive species that may decline or be eliminated from the rangelands (Landsberg *et al.*, 2003). Studies that investigate the combined effect of grazing and competition have been based largely on changes in vegetation density and abundance (e.g., Dayan, *et al.*, 1981; Dovrat *et al.*, 1980; Noy-Meir and Briske, 2002; Tilman, 1988; Loo, 1993). For example, to estimate competitive abilities in vegetation species, relative yields of two species (often yields of above ground biomass) grown at different relative densities, rate of increase in abundance or ability to competitively displace other species from a specific habitat are used (Tilman, 1988). Estimating competitive ability in forage species is particularly challenging because of the unique responses of different plant species to defoliation and competition that may vary in space and over time (Savadogo *et al.*, 2007).

The use of remote sensing for non-destructive estimation of various vegetation parameters such as quality and quantity (e.g., Alvaro *et al.*, 2007; Gamon *et al.*, 1992; Merzlyak *et al.*, 2003; Thenkabail *et al.*, 2004) show that defoliation intensity and competitive interactions among plant species may be studied at regional scale and at less cost than intensive ground surveys. Remote sensing has capabilities for systematic repetitive observations of objects including large areas of the earth's surface in several regions of the electromagnetic spectrum (Campbell, 2002). A remote sensing-based approach, however, will depend on successfully relating spectral characteristics to plant characteristics such as height, lateral spread, growth rate or response to stress and physical damage which are indicated by Grime (1979) to be affected by defoliation and to indicate competitive ability. For example, Alvaro *et al.* (2007) have found strong associations between vegetation spectral indices and crop growth traits such as leaf area per plant (LAP), green area per plant (GAP) and plant dry weight. A number of studies have also applied remote sensing to study vegetation in livestock grazing systems (e.g., Edwards *et al.*, 1999; Kirkpatrick *et al.*, 2005; Landsberg *et al.*, 2003; Mwendera *et al.*, 1997; Numata *et al.*, 2007; Pickup and Chewings, 1988; Wylie *et al.*, 1991), but they have rarely included the aspect of competition.

Spectral vegetation indices may be used to understand the effects of defoliation intensity and competitive dynamics in forage plant species because of their capacity to indicate vegetation abundance and condition (Campbell, 2002). The indices are mostly based on the highly contrasting chlorophyll pigment absorptions in the red region against the high reflectivity of plant materials in the Near Infrared (NIR) region (Tucker, 1979). For example, the NDVI, the physiological reflectance index (PRI) and simple ratio (SR) have been tested for vegetation growth monitoring (e.g., Alvaro *et al.*, 2007; Aparicio *et al.*, 2000; Numata *et al.*, 2007; Sims and Gamon, 2002; Hill *et al.*, 2004; Johnson *et al.*, 1983; Roderick, *et al.*, 2001). Although some of these studies (e.g., Alvaro *et al.*, 2007) have been tested on the performance of individual plant species, the aspect of defoliation intensity and competitive interactions among co-occurring forage species has not been given adequate research attention. Some of the studies show that detailed information can be obtained on the growth and condition of individual plant species using hyperspectral remote sensing. Therefore, hyperspectral remote sensing may be used to study the effects of different defoliation intensities and species mix on the growth performance of forage plants.

Hyperspectral data comprises of contiguous narrow bands of less than 10 nm and provide detailed spectral characteristics of vegetation, thus allowing comprehensive assessment of vegetation parameters (Curran, 1994; Goetz 1985; Thenkabail *et al.*, 2000). Hyperspectral remote sensing has enabled detailed understanding of the spatial distribution of herbivore forage parameters such as species composition, species quality and quantity at finer spatial and temporal scales (e.g., Armitage *et al.*, 2000; Mathur *et al.*, 2002; Mutanga *et al.*, 2003; Schmidt and Skidmore, 2001). Most of the narrow band spectral features and indices have, however, not been investigated for application to defoliation intensity and competitive ability in forage plant species. For example, a widely investigated feature but not yet tested for this phenomenon is the red-edge position (680 nm to 750 nm). This feature is known to correlate with biochemical concentration in plants, especially leaf nitrogen and chlorophyll content, thus enabling the assessment of the development stages and chlorophyll status in vegetation (Horler *et al.*, 1983).

In this study, we investigated whether species cultures (mixed cultures and monocultures) and clipping at high and low clipping intensities significantly affect narrow band spectral reflectance of livestock forage grass, *Dactylis glomerata* (Orchard grass or Cocksfoot grass) and *Lolium multiflorum* (Italian ryegrass) and if changes in the response of spectral reflectance, spectral indices and

the red-edge position indicated competitive ability in the two species. To achieve this objective, we carried out a greenhouse laboratory experiment with the use of a field portable spectroradiometer. First, we analyzed variations in spectral reflectance due to the effect of species cultures and clipping and how the effect changed between clipping events. Secondly, changes in the response of selected spectral reflectance bands, indices and the red-edge position were assessed. Finally, in order to test if the changes in the response relate to competitive ability, the changes in the most sensitive spectral features were related to regrowth in height and dry matter yield of the species under different treatments.

4.2 Methods

4.2.1 Experiment set-up and study species

The experiment set-up described in section 2.2 was used. The same species, *Dactylis glomerata* and *Lolium multiflorum* were used. In addition to the contrasting growth characteristics, the two grasses have different biophysical properties that may affect spectral reflectance. For example, they differ in leaf texture and colour. *L. multiflorum* has a bigger lateral stature and smooth glossy leaves of darker green while *D. glomerata* initially grows slowly but eventually becomes taller, is tufted, and has robust, tough and succulent lighter green bunched coarse leaves (Duke, 1983; Hannaway *et al.*, 1999; Hubbard, 1968).

4.2.2 Clipping treatments and plant growth measurements

Clipping was done at three five-week intervals starting 3 February 2005, when the grass canopy had covered the soil. The clipping at eight weeks, 13 weeks and 18 weeks after sowing are referred to as T1, T2 and T3. In this study, we present analyses based on measurements at 13 weeks (T2) and 18 weeks (T3) only, since the effect of species cultures and clipping was not expected at the first clipping (eight weeks after sowing). Clipping heights of 10 cm and 15 cm above the ground, representing high and low defoliation intensity, respectively, were used in the analysis. Prior to clipping, the height (cm) and dry weight (g) of the plants in each pot were measured as described in section 2.2.3

4.2.3 Spectral reflectance measurements and processing

Before clipping, canopy spectral measurements of each pot were taken using a FieldSpec Pro Full Range (FR) spectroradiometer developed by Analytical Spectral Devices (ASD) Inc., Boulder, Colorado, USA. The FieldSpec has a spectral range from 350 nm to 2500 nm and 10 nm spectral resolution. To ensure stability and uniformity in the measurements, the FieldSpec fiber optic cable of 1.2 m in length and with a 25° full angle field-of-view was mounted on a tripod and fixed through a pistol grip at 90° to the target object. Ten spectral measurements of each pot were taken. For each of the 10 measurements, one measurement of a Spectralon white reference panel was taken. The reference signal obtained was used to calculate reflectance from the measured radiance. The pot was randomly rotated after each of the 10 measurements in order to average directional variation in grass canopy structure and condition within the individual pots. The measurements were taken in a dark laboratory to control for light scattering. The source of illumination was a halogen lamp (50 W quartz) positioned at 45° to the target.

The 10 reflectance measurements for each pot were averaged. The data were resampled to spectral wavebands of HyMap image data to match the measurements with the sensor that was to be used at field level as done in Mutanga and Skidmore (2003) and Thenkabail *et al.* (2004). The HyMap image was flown over Majella National Park, Italy, in 2005 and processed by the German Aerospace Center (DLR). The image has a 4 m spatial resolution and the sensor comprises 126 wavebands operating over the wavelength range 436 nm to 2485 nm, with average spectral resolutions of 15 nm (436 nm to 1313 nm), 13 nm (1409 nm to 1800 nm) and 17 nm (1953 to 2485 nm). The spectral bands from 2010 nm up to 2500 nm of the FieldSpec were not used because of excessive noise. Therefore, 98 wavebands between 436 nm and 2009 nm remained for analysis. For these 98 bands, mean spectral reflectance for the species and clipping combinations at 13 weeks (T2) and 18 weeks (T3) after sowing were derived (Figure 4.1).

4.2.4 Assessing changes in the response of spectral reflectance between T2 and T3

Before testing for changes in the spectral reflectance, the bands that best demonstrated the effect of species cultures and clipping were identified to reduce the dimensionality of the data. Using a general discriminant analysis (GDA) in STATISICA (Stasoft Inc., USA), a forward stepwise model building option was used for wave band

selection. Species cultures and clipping were taken as dependent variables and spectral reflectance as independent predictor variables. A statistical significance level ($P = 0.05$) was used as a basis for inclusion or exclusion of bands in the model at every step. Bands selected by the GDA were then used in a Two-Way ANOVA to test for variation in the spectral reflectance at T2 and T3 due to the effects of species cultures (monoculture and mixed) and clipping, and interaction of the two effects. Wavelength was taken as the dependent variable, while species cultures and clipping were the independent variables. The effect was considered significant at $P = 0.05$.

Using the selected best spectral discriminating bands, we applied a pair-wise Mahalanobis distance (MD) function to compare spectra and to assess changes in the level of discrimination between the spectra of T2 and T3 for the different treatment pairs. An increase in discrimination of the pairs was expected to show decreasing similarity in the growth characteristics of the species, while a decrease was expected to show the contrary. The Mahalanobis distance (D^2) between two entities (j and k) based on P variables is defined by McGarigal *et al.* (2000) as follows:

$$D^2 = (x_j - x_k)^T \Sigma^{-1} (x_j - x_k) \quad (\text{Eq. 4.1})$$

where Σ is the pooled within-groups variance-covariance, x_j is the vector of scores for the i th entity, and x_k is the vector of scores for the j th entity. An F -test was used to establish the level of significance (at $P = 0.05$) of the differences in the Mahalanobis distance.

4.2.5 Assessing changes in the response of spectral reflectance, indices, and the red-edge position

Changes in the response of vegetation indices, reflectance at two specific wavebands (694 nm and 800 nm) and the red-edge position were assessed for *D. glomerata* and *L. multiflorum* in the monocultures and the mixed cultures under high and low clipping intensities. Spectra for each treatment combination were first smoothed using the Savitsky-Golay algorithm (Savitzky and Golay, 1964). The vegetation indices that were computed included the Carter index, NDVI, simple ratio, PRI and the ratio of Transformed Chlorophyll Absorption in Reflectance Index to the Optimized Soil-Adjusted Vegetation Index (TCARI/OSAVI). Table 4.1 presents a summary of the indices and selected reflectance at 694 nm and 800 nm, the formulas used in the calculations and the rationale and references. Finally, the red-edge position values were extracted. A

detailed description of the indices and red-edge position calculations is provided below.

Percentage increase in spectral features for different treatment combinations was compared. A Two-Way ANOVA was used to test if indices, reflectance at 694 and 800 nm, and the red-edge position at T2 were significantly different ($P \leq 0.05$) from those at T3 for the different pairs of species and clipping treatments. To test if the change in growth characteristics explained the response in the spectral variables, values for the most sensitive index were compared with height and dry matter.

4.2.5.1 The Carter index

Carter (1994) identified narrow band reflectance at 695 nm divided by reflectance at 760 nm to be an index strongly correlated with plant stress:

$$CI = \left(\frac{R_{695}}{R_{760}} \right) \quad (\text{Eq. 4.2})$$

where R_{695} is the reflectance at 695 nm and R_{760} that at 760 nm. In all the subsequent formulas presented, R_n is the reflectance at n nm.

At 695 nm and 710 nm absorption by chlorophyll *a* and *b* is relatively weak and leaf chlorophyll content begins to decline with the occurrence of stress. Leaf reflectance increases first at these wavelengths but as chlorophyll continues to decline in these bands, reflectance increases in the bands of high chlorophyll and pigment absorption such as at 420 nm, and 670 nm. The index may therefore indicate stress levels depending on the species and clipping treatments.

4.2.5.2 NDVI

The Normalized Difference Vegetation Index (NDVI) is a widely used index for monitoring vegetation condition. It is based on the high reflection of living vegetation in the near infrared region of the electromagnetic spectrum and the relatively low reflection in the visible red wavelength (Gitelson, 2004):

$$NDVI = \left(\frac{R_{830} - R_{670}}{R_{830} + R_{670}} \right) \quad (\text{Eq. 4.3})$$

Studies (e.g., Mutanga and Skidmore, 2004) show that narrow band NDVI better estimates biomass than the conventional broad band NDVI which tend to saturate at high biomass levels.

4.2.5.3 Simple Ratio

The simple ratio (SR) was derived for estimation of LAI in dense forests (Jordan 1969). The SR has been useful for other vegetation types including grass biomass measurements, especially the narrow band SR:

$$SR = \left(\frac{R_{830}}{R_{680}} \right) \quad (\text{Eq. 4.4})$$

Alvaro *et al.* (2007) have associated the SR with cereal crop growth traits including plant dry weight, while Mutanga and Skidmore (2004) have associated it with biomass.

4.2.5.4 Physiological reflectance index

The physiological reflectance index (PRI) has been associated with the xanthophyll-cycle pigment changes, ratio of carotenoids to chlorophyll content, photosynthetic light use efficiency, and LAI (Gamon *et al.*, 1992; Peñuelas *et al.*, 1995; Barton and North, 2001). The PRI is defined as:

$$PRI = \left(\frac{R_{531} - R_{570}}{R_{531} + R_{570}} \right) \quad (\text{Eq. 4.5})$$

The carotenoids (yellow pigments) together with chlorophyll contribute energy to the photosynthetic system and provide information concerning the physiological status of leaves, thus, carotenoid/chlorophyll ratios reveal changes in growth and stress in vegetation (e.g., Sims and Gamon, 2002).

4.2.5.5 TCARI/OSAVI

The ratio of the Transformed Chlorophyll Absorption in Reflectance Index/Optimized Soil-Adjusted Vegetation Index (TCARI/OSAVI) was devised by Haboudane *et al.* (2002) to predict chlorophyll content from remote sensing data while minimizing the influence of variations in LAI, and the effects of underlying soil background. The formula is expressed as follows:

$$TCARI/OSAVI = \left(\frac{3 \times [(R_{700} - R_{670}) - 0.2 \times (R_{700} - R_{670}) \times (R_{700}/R_{670})] R_{531} - R_{570}}{(1 + 0.16) \times (R_{800} - R_{670}) (R_{800} + R_{670} + 0.16)} \right) \quad (\text{Eq. 4.6})$$

4.2.5.6 The red-edge position

The red-edge position (REP) is described by Horler *et al.* (1983) as the inflection point between the chlorophyll absorption feature in the red region and leaf scattering in the NIR region. The REP has been used to assess leaf chlorophyll, LAI and biomass (e.g., Cho *et al.*, 2006; Fillella and Peñuelas, 1994; Horler, 1983; Mutanga and Skidmore, 2007; Patel *et al.*, 2001). Guyot and Baret (1988) found that the red-edge position was associated with plant phenology and health status. Green leaves with high chlorophyll concentration show the red-edge position progressively shifting toward longer wavelength with increasing chlorophyll and LAI.

A linear four-point interpolation method (Guyot and Baret, 1988) was used to extract the REP. The method uses a straight line centred near the midpoint between the reflectance at 780 nm in the NIR and the reflectance at 670 nm as the reflectance minimum of the chlorophyll feature. Usually, bands at 670 nm, 700 nm, 740 nm and 780 nm are used but, since the data used in this study were resampled to the HyMap image data, the corresponding image bands at 665 nm, 695 nm, 740 nm and 786 nm were used. A two-step equation is required to derive the REP as follows:

(a) Calculation of the reflectance at the inflexion point (R_{re}):

$$R_{re} = (R_{665} + R_{786})/2 \quad (\text{Eq. 4.7})$$

(b) Calculation of the REP:

$$REP = 695 + 44 \left(\frac{R_{re} - R_{695}}{R_{740} - R_{695}} \right) \quad (\text{Eq. 4.8})$$

where 695 and 44 are constants resulting from interpolation in the 695 nm to 740 nm interval.

Table 4.1 Spectral indices used in the study, rationale and references

Spectral index	Rationale for application	Reference
Carter index (CI)	Chlorophyll sensitive, stress detection	Carter, 1994
Normalized difference vegetation index (NDVI)	Vegetation greenness, leaf area index (LAI), and fraction of photo-synthetically active radiation	Rouse <i>et al.</i> , 1974; Tucker, 1979
Simple ratio (SR)	Biomass-sensitive, green area per plant	Jordan, 1969
Photochemical /physiological reflectance index (PRI)	Xanthophyll-cycle pigment changes, carotenoids/chlorophyll content, photosynthetic light use efficiency, and LAI	Gamon <i>et al.</i> , 1992; Peñuelas <i>et al.</i> , 1995; Barton and North, 2001
TCARI)/OSAVI	Chlorophyll sensitive index and less affected by soil background and variations in LAI and solar zenith angle	Haboudane <i>et al.</i> , 2002
R ₆₉₄	Chlorophyll-sensitive, stress detection	Carter and Miller, 1994
R ₈₀₀	Anthocyanin-sensitive, LAI-sensitive	Merslyak <i>et al.</i> , 2003

4.3 Results

4.3.1 Changes in spectral reflectance between T2 and T3

Variation in spectral reflectance due to the effect of species cultures (mixed and monocultures) and clipping height above the ground (10 cm: high intensity and 15 cm: low intensity) are presented. The spectral reflectance significantly varied between the two clipping events at 13 weeks (T2) and 18 weeks (T3) after sowing and in the different regions of the spectrum (Table 4.2). Mean spectral reflectance for the species and clipping combinations at T2 and T3 are shown in Figure 4.1. The reflectance curves of the mixed cultures appear to be more similar to those of *L. multiflorum* than of *D. glomerata*. Visual differentiation of the spectra for *D. glomerata*

shows more distinct separability between the spectra of T2 and T3 especially in the near infrared (NIR) region. Figure 4.1 further shows that clipping the species at low intensity resulted in higher reflectance than clipping at high intensity. In the mixed species, the visual differentiation of the spectra between T2 and T3 seems less for the low clipping intensity than for high clipping intensity especially in the red-edge position. In contrary, the T2 and T3 spectra for *D. glomerata* clipped at low intensity appear more separable than for spectra of the species that were clipped at high intensity especially in the NIR.

The number of bands that showed significant effect of species culture and clipping on spectral reflectance decreased and extended from the visible (red) to the NIR region. Table 4.2 shows the best discriminating bands obtained from the general discriminant analysis and the results of the Two-Way ANOVA on the effect of species cultures and clipping on the selected best discriminatory bands at 13 weeks (T2) and 18 weeks (T3) after sowing. Eight discriminatory bands at T2 were between 525 nm and 846 nm, mostly in the visible (red) region of the spectrum, and to a lesser extent in the NIR region. In comparison, at T3 the number of discriminating bands was reduced to five. These were located mainly in the NIR, and to a lesser extent in the visible (red) region.

The Two-Way ANOVA results showed that the spectral reflectance at T2 and T3 were significantly different largely due to the effect of species cultures (monoculture and mixed), clipping, and the interaction of the two. Table 4.2 shows that at T2 the effect of species cultures was significant ($P < 0.05$) in the visible (red) region, whereas clipping effect was highly significant ($P < 0.001$) in the NIR. At T3, the effect of species cultures was highly significant in all the bands selected for analysis ($P < 0.001$). On the other hand, the effect of clipping at T3 was significant ($P < 0.05$) in one band of the visible region and the NIR. The number of bands in which clipping affected the spectra appear to increase over time. At T2, the interaction effect of the species cultures and clipping was significant at only 695 nm ($P < 0.001$).

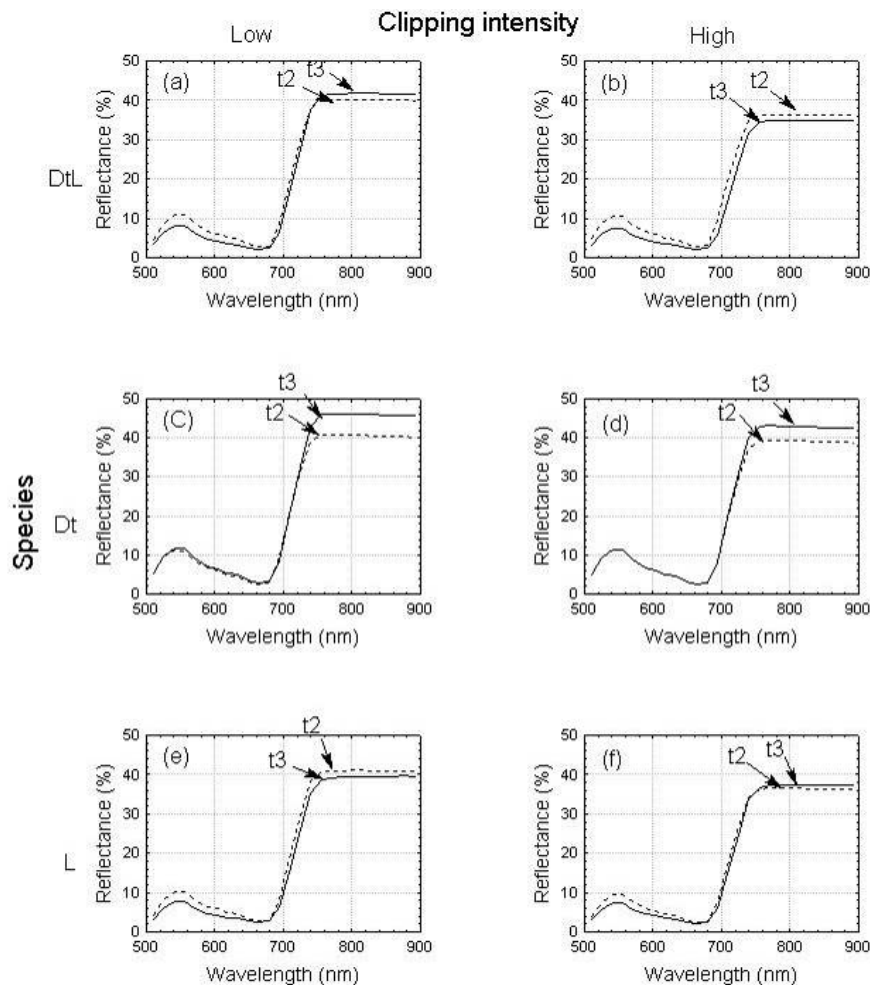


Figure 4.1 Mean reflectance spectra in species cultures (mixed and monocultures) at low (15 cm) and high (10 cm) clipping intensities at 13 weeks (T2) and 18 weeks (T3) after sowing. Species cultures: Dt = *D. glomerata*, L = *L. multiflorum*, and DtL = mixture of Dt and L.

The results show that between the two clipping events, species culture and clipping affect biophysical and biochemical properties of the grasses in different regions of the spectrum. Species cultures possibly dominate the effect on the physiological and biochemical variables at T2, whereas clipping progressively dominates the effect on leaf/canopy structure.

Table 4.2 *P*-values for the effect of species cultures, clipping, and the interactive effects of species and clipping on the selected best discriminatory bands at 13 weeks (T2) and 18 weeks after sowing (T3)

Wave-length	Spectral region	Treatment effect <i>P</i> -values		
		Species culture	Clipping	Species x clipping
T2: 13 weeks after sowing				
525	Visible (red)	0.000**	NS	NS
542	Visible (red)	0.000**	NS	NS
634	Visible (red)	NS	NS	NS
663	Visible (red)	NS	NS	NS
679	Visible (red)	0.037*	NS	0.048*
695	Visible (red)	0.000**	NS	0.000*
815	NIR	NS	0.000**	NS
846	NIR	NS	0.000**	NS
T3: 18 weeks after sowing				
437	Visible (red)	0.000***	0.092	NS
679	Visible (red)	0.000***	0.018*	NS
1007	NIR	0.000***	0.002**	NS
1038	NIR	0.001**	0.002**	NS
1083	NIR	0.000***	0.002**	NS

Significance levels: * = 0.05, ** = 0.001, *** < 0.001.
NS = Not significant

Mahalanobis distances between the different treatment pairs showed a decreasing level of discrimination between the different pairs of spectra at T2 and T3 (Table 4.3). Table 4.3 shows that at T2, distances ranged between 3 and 8, whereas at T3 the distance decreased to ranges between 1 and 7. Mahalanobis distances at T2 were larger than at T3, differences being significant for all compared pairs ($P < 0.05$) (results of the *F*-test for the significance of the Mahalanobis distance are not shown here). According to Table 4.3, the highest decrease (34%) in the Mahalanobis distance was between the spectra of dactylic clipped at low intensity (Dt_Low) and Lolium clipped at low intensity (L_Low). This decrease was the highest at

both T2 and T3, involving the two different species at the same clipping height, suggesting a decreasing species effect.

The decreasing level of spectral discrimination between the pairs suggests that the similarity between the species under different treatments was increasing. The results also suggest that T2 may be the better time to detect the effect of cultures and clipping treatments on reflectance than T3.

Table 4.3 Mahalanobis Distance between species –clipping pairs at T2 (13 weeks after sowing) and T3 (18 weeks after sowing). Treatments: Species (DtL = mixture; Dt = *D. glomerata*; L = *L. multiflorum*) and Clipping (Low = 15 cm; High = 10 cm above the ground).

<i>Species/Clipping treatment</i>	<i>Mahalanobis Distance</i>				
T2: 13 weeks after sowing					
	DtL_Low	DtL_High	Dt_Low	Dt_High	L_Low
DtL_High	7.12				
Dt_Low	7.15	3.32			
Dt_High	3.50	7.52	6.56		
L_Low	3.04	7.48	8.16	5.84	
L_High	2.66	6.67	7.60	4.62	3.01
T3: 18 weeks after sowing					
	DtL_Low	DtL_High	Dt_Low	Dt_High	L_Low
DtL_High	1.48				
Dt_Low	5.22	4.64			
Dt_High	4.61	3.97	1.42		
L_Low	1.53	2.44	6.37	5.84	
L_High	1.19	1.38	5.57	5.08	1.50

4.3.2 Changes in the response of spectral reflectance, indices, and the red-edge position

Responses in all spectral indices, specific reflectance at 694 and 800 nm and red-edge positions changed significantly between T2 and T3. Table 4.4 shows the mean spectral values for the different species cultures and clipping treatment pairs at T2 and T3, whereas Figure 4.2 shows changes in the spectral values between the two clipping events. Figure 4.3 shows mean spectral values and pairs of treatments that significantly differed according to the Two-Way ANOVA and Scheffé *post hoc* test.

The PRI showed the highest change in the values (average of 75% increase) between T2 and T3. The change was highly significant ($F(10, 198) = 38.211, p < 0.0001$), and involved all the treatment pairs, suggesting sensitivity to increasing photosynthetic material and decreasing physiological stress. This coincided with a significant increase in the Carter index ($F(10, 198) = 7.2799, p < 0.0001$). A significant increase in the R_{694} occurred as well ($F(10, 198) = 15.474, p < 0.0001$), mainly for the mixed species clipped at high intensity. This suggests sensitivity of the R_{694} to increasing stress in the high clipping intensity that was not detected by the preceding indices. R_{800} increased significantly ($F(10, 198) = 4.4044, p < .0001$) but none of the pairs showed significant changes. The red-edge position shifted significantly to the NIR region ($F(10, 198) = 33.859, p < 0.0001$) in all pairs of species and clipping treatments except for monocultures of *D. glomerata* clipped at low intensity (15 cm). The NDVI values increased significantly ($F(10, 198) = 2.3667, p < 0.05$), but the change percentage was negligible and only significant in the mixed species clipped at high intensity. A significant decrease was shown in TCARI/OSAVI ($F(10, 198) = 16.386, p < 0.0001$) mostly for *D. glomerata* species. The values of the SR and R_{800} significantly changed but were not significant for specific pairs of treatments.

Therefore the PRI, Carter index, R_{694} , TCARI/OSAVI and REP, in order of sensitivity, may be used to estimate the effect of different species culture and defoliation treatments on the growth and competitive ability of the forage species investigated.

Table 4 Spectral index values for the different species cultures and clipping intensity at T2 and T3
Treatments: Species (DtL = mixture; Dt = *D. glomerata*, L = *L. multiflorum*) and Clipping (Low = 15 cm; High = 10 cm above the ground).

Indices	Treatments																	
	DtL_Low			DtL_High			Dt_Low			Dt_High			L_Low			L_High		
	T2	T3		T2	T3		T2	T3		T2	T3		T2	T3		T2	T3	
Cartier index	4.802	6.604		3.778	5.996		4.291	5.436		4.757	5.310		5.111	6.242		4.944	6.245	
NDVI	0.863	0.887		0.838	0.871		0.862	0.867		0.857	0.869		0.865	0.870		0.866	0.876	
SR	13.561	16.739		11.367	14.563		13.453	14.036		12.966	14.325		13.834	14.427		13.934	15.184	
PRI	-0.005	0.011		0.041	0.010		0.053	0.017		0.012	0.018		-0.014	-0.004		-0.006	0.002	
REP	0.714	0.716		0.712	0.716		0.712	0.715		0.713	0.714		0.714	0.716		0.714	0.716	
TCARI/OSAV	21.605	22.525		24.242	22.506		19.783	18.960		15.252	13.714		21.992	21.754		13.460	13.463	
I																		
R694	8.351	6.241		9.609	5.755		9.514	8.465		8.262	8.093		7.987	6.206		7.346	5.887	
R800	40.273	41.774		36.443	34.860		40.762	46.170		39.266	42.999		41.087	39.451		36.541	37.326	

Table 5 Physiological reflectance index (PRI), dry matter (DM) and height for species and clipping treatments at T2 and T3. Species: DtL = mixture; Dt = *D. glomerata*; L = *L. multiflorum*. Clipping: Low = 15 cm; High = 10 cm above the ground

Species	Clipping	Mean DM (g)		Mean DM (g)		Avg. Height (cm)		Avg. Height (cm)		PRI index		PRI index	
		T2	T3	T2	T3	T2	T3	T2	T3	T2	T3	T2	T3
DtL	Low	21.3	22.6	30.7	32.7	-0.005	0.011						
DtL	High	20.2	22.4	29.4	31.5	0.041	0.010						
Dt	Low	13.3	15.8	37.6	37.7	0.053	0.017						
Dt	High	14.6	17.0	36.6	36.3	0.012	0.018						
L	Low	12.4	14.0	32.0	30.7	-0.014	-0.004						
L	High	14.7	15.1	29.3	31.0	-0.006	0.002						

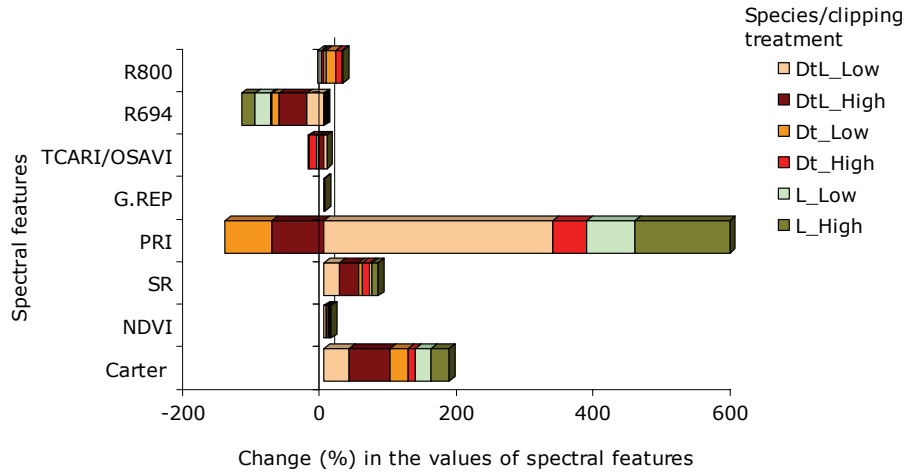


Figure 4.2 Change (%) in the values of spectral features between T2: 13 weeks and T3: 18 weeks after sowing for the different species and clipping treatments. Legend codes: Dt = *Dactylis glomerata*; L = *Lolium multiflorum*, and DtL = mixture of Dt and L). Codes for spectral features: NDVI = normalized difference vegetation index, SR = simple ratio, PRI = photochemical/physiological reflectance index, G.REP = red-edge position using the Guyot and Baret (1988) equation. TCARI/OSAVI is the ratio of the Transformed Chlorophyll Absorption in Reflectance Index (TCARI) to Optimized Soil-Adjusted Vegetation Index. "R" in R₆₉₄ and R₈₀₀ denotes reflectance at the specified wavelength.

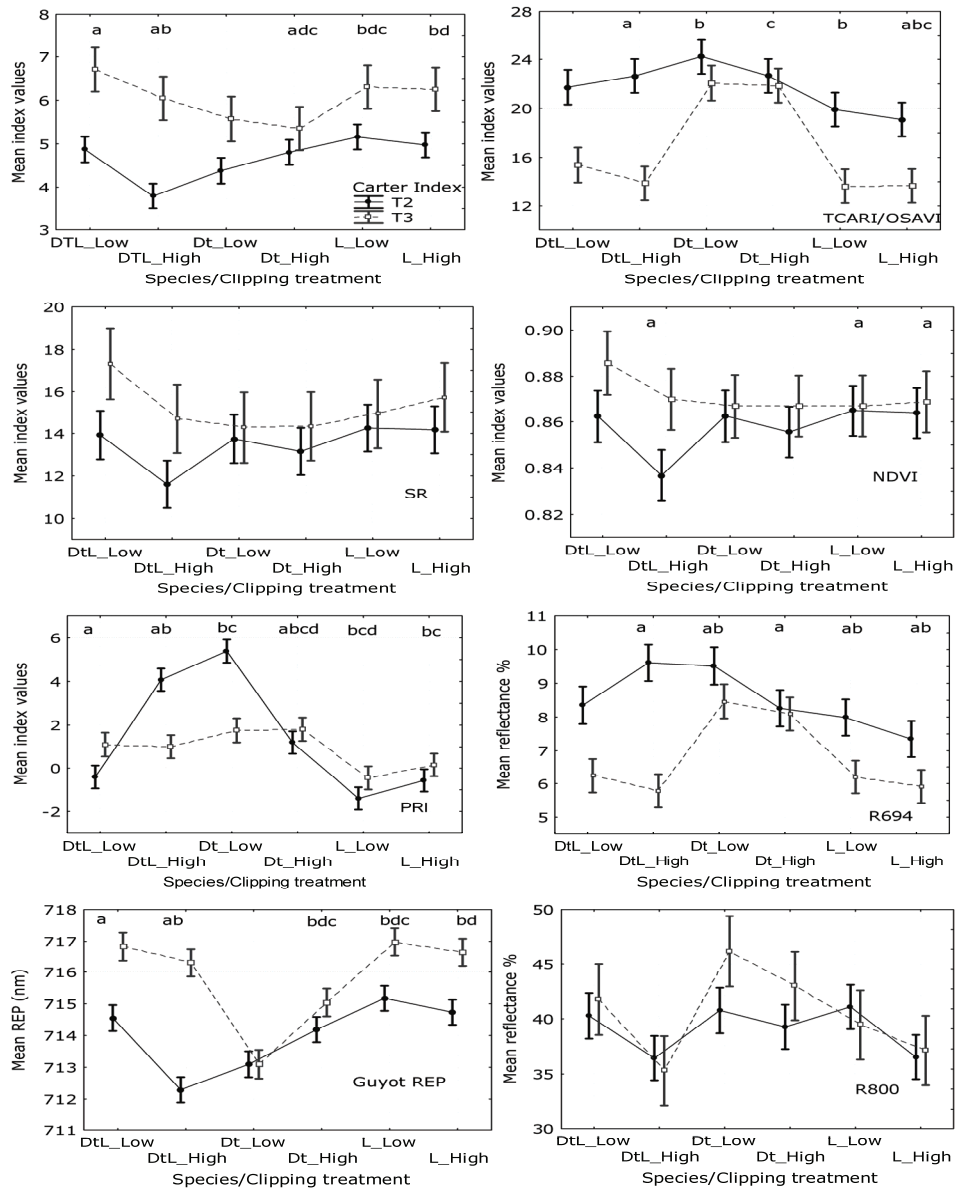


Figure 4.3 Mean values of spectral features for different combinations of species/clipping treatments at T2: 13 weeks after sowing and T3: 18 weeks after sowing. The legend for the Carter index (top-left) applies to all the graphs. The PRI values are transformed (multiplied by 100) for scaling purposes. Legends for species cultures/clipping treatments and spectral features are contained in Figure 4.2. Letters on top of the graphs correspond to pairs that were found significantly different according to the ANOVA Scheffé *post hoc* test ($P \leq 0.05$).

4.3.3 Relationship between the PRI and growth variables

The change in the response of the PRI (the most sensitive spectral feature) is associated with plant height and dry matter yield of *D. glomerata* and *L. multiflorum*. A negative relation was shown between the PRI and dry matter (g) and height (cm) at T2 while a positive relation was shown at T3. Table 4.4 and Figure 4.4 show a negative relationship between the PRI and average height above 32 cm and a negative relation between PRI and dry matter values above 17 g. at T2. At T3, a linear positive relationship is shown for both height and dry matter. The changes in the PRI for specific pairs of species and clipping treatments may be related to the differences in the increase in dry matter and height of *L. multiflorum* and *D. glomerata* (Table 4.4). This suggests that the PRI may increase depending on increased photosynthetic material.

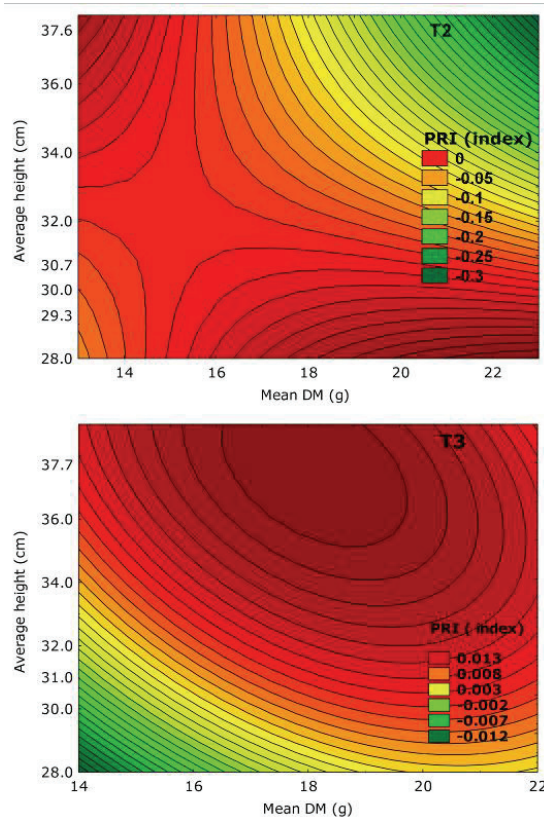


Figure 4.4 3D contour plots showing changes in the response of the PRI to the effect of height (cm) and dry matter (g) in the species at T2: after 13 weeks (top) and T3: after 18 weeks (bottom).

4.4 Discussion

The species cultures (mixed and monocultures) and clipping intensity (10 cm referred to as high and 15 cm referred to as low) distinctively affected the spectra at T2: 13 weeks and T3: 18 weeks after sowing and the effect varied in the two regions of the spectrum (the visible and NIR).

From the visual interpretation of Figure 4.1, we found that the reflectance of the mixed cultures was more similar to that of *L. multiflorum* than to the reflectance in monocultures of *D. glomerata*, possibly because *L. multiflorum* was dominating in the mixed species. In addition, the previous chapters (Chapter 2 and Chapter 3), show that *L. multiflorum* obtained higher dry matter yield than *D. glomerata*, when the two were grown in mixtures. Reflectance in *D. glomerata* was higher than in the other species, especially in the NIR region whereas the mixed species seemed separable in the red-edge position. The differentiation of spectra at T2 and T3 for *D. glomerata* clipped at low intensity also appeared to be greater than at high clipping intensity, particularly, in the NIR. The results suggest that the red-edge position may be sensitive to the changes in regrowth of the species, but not to the properties that may have led to high reflectance of *D. glomerata* in the NIR. Such properties may include pigmentation and leaf/canopy structure (Campbell, 2002; Sims and Gamon, 2002). Previous work (e.g., Duke, 1983; Hannaway *et al.*, 1999; Hubbard, 1968) indicate that the two grasses have contrasting growth characteristics that may affect spectral reflectance (e.g., height and lateral stature) and differ in leaf texture and colour. These properties are potential subjects of future research.

Since the species culture showed significant effects in the visible region at T2 while the effect of clipping affected the spectra mostly in the NIR at T3 (Table 4.2), it is possible that the species cultures had a greater effect on the physiological and biochemical variables at T2, while clipping had greater effect on leaf/canopy structure. This may correspond to the effect of species and clipping on pigment and physiological conditions dominating at the initial measurement time, while the effect on canopy structure dominated later in the growth of the two grasses. This means that at T3, the effect of clipping (defoliation damage to the leaf structure) may have played a more significant role.

Different growth stages as a result of differences in germination time may also explain the differences in spectra of the two species. In this study, *L. multiflorum* germinated two weeks earlier than *D. glomerata*.

Consequently, the species were at different stages of growth by the time of data collection. Differences in growth stages have explained the variation in plant growth and spectral response (e.g., Alvaro, *et al.*, 2007). The earlier germination of *L. multiflorum* may have enhanced its growth against that of *D. glomerata*. Other studies, (e.g., Espigares *et al.*, 2004; Fetene, 2003; Humphrey and Schupp (2004), highlight the competitive advantage of early germination. Considering Grime (1979) and the results shown in Chapter 2 and 3 of this thesis, early germination was one of the suggested reasons why *L. multiflorum* obtained higher dry matter yield and regrowth rate than *D. glomerata*, thus the differences in spectral reflectance.

As the region of discrimination shifted from the visible to the NIR, and the dry matter yield and height increased, the level of discrimination of the different pairs of spectra for the various treatments declined (Table 4.2 and 4.3). The change in the level of discrimination also shows that the differences in the spectra of the different species were decreasing, possibly due to increasing similarity in the phenological developments of the species (Campbell, 2002). This suggests that the initial measurement time (T2: after 13 weeks) may be the better time to detect the effect of the treatments on reflectance than T3. Further investigation is needed on how development stages of the different species relate to the effects of different defoliation intensities and species mixes.

Of the spectral features tested, the highest percentage change was shown in the PRI. Furthermore, the PRI showed a linear positive response to both height and dry matter at T3, which was not the case at T2. The positive sensitivity to both dry matter yield and height with time shows that the PRI increased with increased photosynthetic material. Other authors (e.g., Baghzouz *et al.*, 2006) found that changes in spectral parameters corresponded to changes in plant cover, biomass and productivity as a result of temporal variations in nitrogen supply, water stress and clipping. The change observed in this study suggests prominent changes in the ratio of carotenoids to chlorophyll between the two clipping times. A relationship has been found between the PRI and the carotenoid/chlorophyll ratio and linked to leaf development (Peñuelas *et al.*, 1994; Sims and Gamon, 2002). The change was mostly shown for the mixed species possibly due to differences in the response of growth variables (dry matter and height) of *L. multiflorum* and *D. glomerata*. The increase may also be attributed to the high regrowth of *L. multiflorum* in comparison with *D. glomerata*.

For the application of this study, the PRI may, therefore, be the best index to monitor the effects of species culture and defoliation in the initial (vegetative) stages of co-occurring forage species. The PRI has shown this potential as it has been widely used in light use efficiency models to predict pasture growth (e.g., Hill *et al.*, 2004; Roderick *et al.*, 2001). The value of the PRI may also lay in its ability to reveal short-term changes in actual photosynthetic efficiency in well developed canopies where other indices such as NDVI are least sensitive (Gamon *et al.*, 1992).

Other spectral features may offer useful options for monitoring the effects of defoliation intensity and species mix on the growth performance of forage species. Our study shows that the Carter index, R_{694} , TCARI/OSAVI, the red-edge position and the best discriminating bands at 695 nm are also useful options. The red-edge position is of particular interest because of its proven ability to detect changes in spectral response to the growth of a number of crops (e.g., Collins, 1978; Patel *et al.*, 2001). Collins (1978) shows that as crops approach maturity, the position of the chlorophyll absorption edge shifts toward longer wavelength, a change referred to as the red shift attributed largely to increase in LAI.

In other studies (e.g., Alvaro *et al.*, 2007; Aparicio *et al.*, 2000; Skidmore and Mutanga, 2004), the simple ratio showed significant correlation with LAI and biomass. A strong relationship between NDVI and primary production over time has been found for grasslands (e.g., Fuller, 1998). These findings suggest that the simple ratio and NDVI may perform better in other situations. Further research to estimate these changes should investigate the relations between spectral variables and other factors that influence vegetation reflectance such as view angle, leaf/canopy structure and colour (Alvaro *et al.*, 2007; Barton and North, 2001) at field landscape level.

4.5 Conclusions

Spectral variables are affected by species cultures and clipping. To study regrowth capacity and competitive ability of forage species between defoliation events, the PRI, the Carter index, R_{694} , TCARI/OSAVI, the red-edge position and the best discriminating bands at 695 nm can be used.

The number of bands in which the effects of species culture and clipping on spectra was significant ($P < 0.05$) extended from the visible (red) to the NIR region of the spectrum. The two treatments distinctively affected the spectra in the different regions of the

spectrum over time, whereby the species cultures had significant effect ($P < 0.05$) in the visible (red) region initially, while clipping effect was highly significant ($P < 0.001$) only in the NIR region. The effect was shown in more bands at a later time both in the visible and the NIR. The effect of species cultures may have dominated the physiological and biochemical variables at T2, whereas the clipping progressively dominated the effect on leaf/canopy structure.

A high increase in the PRI suggested that pigment and physiological effects on spectra increased, possibly because of increased photosynthetic material resulting from the growth in dry matter and height of the two grasses (Table 4.5). The spectral response in mixed cultures was more comparable with the monoculture of *L. multiflorum* than with that of *D. glomerata*. This suggests that the shifting of the effects to the shortwave region and the changes in the PRI that occurred mostly in the mixed cultures were possibly related to the fast growing and higher competitive ability of *L. multiflorum* that was shown in the mixed cultures. The response of the PRI to height and dry matter in the species reflected this possibility, because these growth characteristics are some of the indicators of competitive ability.

This study shows possibilities for the use of hyperspectral remote sensing in monitoring livestock grazing intensity and competitive ability of different forage plant species. If the relationship between height and dry matter and the spectral reflectance features is tested further and found to be consistent at field level, then the approach used may be a simpler and quicker alternative to the existing canopy height and pasture growth models. This would be a vital contribution to efficient assessment of the condition and spatial patterns of herbivore forage vegetation species at field level.

While hyperspectral remote sensing may be the appropriate tool, the contribution of knowledge from local pastoralists and rangeland ecologists who have intimate knowledge of the rangelands needs to be investigated. This is the subject of the investigation in the next chapter.



CHAPTER 5

Testing local knowledge and spatial tools for PGIS-based livestock grazing intensity mapping

Based on: Representation of uncertainty and integration of PGIS-based grazing intensity maps using evidential belief functions J. Bemigisha, E.J.M. Carranza, A.K. Skidmore, M. McCall, C. Polce and H.H.T. Prins [In review, Transactions in GIS]

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Abstract

Local participatory knowledge products are often used when empirical studies are limited by lack of directly measurable data. The quality may be testable by triangulation and comparisons with data from other objective sources and the use of spatial mapping tools. In a study to classify livestock grazing intensity in Majella National Park, Italy using participatory geographic information systems (PGIS), we encountered a problem of integrating different maps and ascertaining their reliability. The use of spatial evidential belief functions (EBFs) and Dempster's rule of combination to represent classification uncertainty and integrate the PGIS-based maps was investigated. The integrated grazing intensity map was then compared with a grazing suitability index. The index was derived using spatial multicriteria evaluation (SMCE) of a combination of landscape factors that influence grazing distribution. We found that the lowest degree of classification uncertainty was associated with maps in which the distribution of palatable vegetation species" as the mapping criterion. This criterion may be the appropriate standard measure for grazing intensity but other parameters such as vegetation quantity and a livestock utilization factor need to be integrated. The comparison of the grazing suitability index and intensity maps showed a weak correlation ($r= 0.35$ ($p < 0.01$)) but the data indicated that the higher the grazing suitability index, the higher the grazing intensity class. The study suggests that local participants, especially local experts have the capability to produce data and synthesize spatial variables for mapping grazing intensity and grazing suitability evaluation but this may be improved by applying EBFs and SMCE in the PGIS process and ensuring adequate participation of local pastoralists.

5.1 Introduction

Improved understanding of the ecological effects of free-ranging and herded livestock has been severely hampered by limited data on their spatio-temporal distribution (Turner and Hiernaux, 2002). The spatial distribution of livestock use varies according to various factors. For example, at landscape level, these include vegetation species composition, vegetation structure (life forms), vegetation density or quantity, terrain, water, and human infrastructure (Stuth, 1991). At agro-ecological level, the factors include substrate rock type, soil and climate (Van Gils, 1984). Owing to the interactions of these factors with different livestock densities and behaviour the resulting spatial patterns also vary (Kohler *et al.*, 2006). The spatial representation of livestock distribution is therefore more likely to vary and increase in uncertainty as the number of factors to be considered in the analysis increases. This is particularly challenging for local knowledge-based mapping (Jansen, 1998). In this study, local knowledge refers to knowledge from local pastoralists and local experts. The definitions of these kinds of knowledge are given in chapter 1 (Section 1.3.3). Local knowledge is valuable, especially when models based on empirical studies are limited by data or are not available (e.g., Ho and Smith, 1997; Store and Kangas, 2001; Van der Hoeven *et al.*, 2004).

Mapping or classifying grazing intensity is commonly done using scientific approaches that may not easily be understood by local participants. Parameters as measures or proxies for grazing intensity include animal units/ha (AU/ha) (Heitschmidt and Stuth, 1991), stocking density (Verweij, 1995) and stocking rate (Tainton *et al.*, 1999). These measures are not standardized and the proxies, particularly animal density, are sometimes used as direct measures of grazing intensity. For example, the definition of stocking rate has various expressions (Tainton *et al.*, 1999). Bakker (1989) evaluates various grazing intensity measures, including dunging intensity and distance to water points, and recommends the use of forage condition measured against a livestock utilization factor. On the other hand, the widely used optimal foraging and diffusion estimation procedures assume that livestock density declines with distance from livestock concentration points such as water points, villages, and camps (Turner and Hiernaux, 2002). Turner and Hiernaux (2002) suggest a geographic information system (GIS) approach that involves local livestock keepers' spatial knowledge of land use, topography, vegetation, settlements and water points. The parameters and variables for estimating grazing intensity are therefore various and not straightforward. Standardized classification systems are needed

for common understanding and for the integration of diverse expert and local knowledge.

Local spatial knowledge may be composed using participatory GIS (Rambaldi *et al.*, 2006). Participatory geographic information systems (PGIS) aim to strengthen conventional land use and land cover mapping, particularly by integrating diverse knowledge in a spatial context (e.g., Turner and Hiernaux, 2002; Scholz *et al.*, 2004; Close and Hall, 2006; Minang and McCall, 2006). However, PGIS offers more than conventional GIS and participatory tools such as participatory rural appraisal (PRA). This is because PGIS combines the GIS functionalities of spatial data acquisition, storage, retrieval, manipulation and analysis with the PRA technique of capturing essential information local people (e.g., land users and land managers), who have intimate knowledge of their environment (Gonzalez, 2002). Various spatially oriented questions can therefore be answered using local knowledge (e.g., Agrawal, 1995; Close and Hall, 2006; Lawas and Luning, 1996).

Spatial multicriteria evaluation (SMCE) is another spatial tool that may provide a framework for PGIS-based mapping and evaluation of choice decisions on land. The SMCE tool integrates the GIS capabilities of data acquisition, storage, retrieval, manipulation and analysis and the capabilities of multicriteria decision-making techniques for aggregating the geographical data and the decision maker's preferences into standardized values (Malczewski, 1999). These tools respond to the need for scoping and analyzing multi-factor interactions, an opportunity that may benefit local participatory mapping processes, but, to our knowledge, no integrated application of SMCE and PGIS has been reported for livestock grazing distribution mapping.

Map users depend upon the veracity and reliability of the data that the maps contain (Evans, 1997). The International Organization for Standardization (ISO) 19113 standard on geospatial data quality recommends logical consistency as one of the verification measures of spatial data because it shows the degree of adherence to logical rules of data structure, attribution, and relationships (Vallieres *et al.*, 2006). Most, if not all, PGIS-based classifications of land use or land cover are faced with the question of how to process and integrate human knowledge, which to a certain degree is incomplete, imprecise, vague or uncertain (Zadeh, 1983; Ding and Kainz, 1998). This question is becoming increasingly relevant as participatory-based mapping activities find their way into spatial analysis and modelling (e.g., Walker *et al.*, 1999; Ozesmi and Ozesmi, 2004).

In general, there are two forms of uncertainty associated with maps: stochastic and systemic (Carranza *et al.*, 2005). On the one hand, stochastic uncertainty is related to the insufficiency or inefficiency of spatial data for a specific use. On the other hand, systemic uncertainty arises from the analytical procedures involved in evaluating all the data or information used for classification. In PGIS-based mapping, systemic uncertainty is associated with either the experts' or the local people's assessment of parameters or criteria of interest. A uniform representation and evaluation of systemic uncertainty is therefore desirable in, for example, PGIS-based livestock grazing intensity classification.

In this study, we deal with uncertainty in PGIS-based maps produced by local rangeland experts. The application of fuzzy set theory to local knowledge-based classification shows the attempt to deal with situations in which spatial data based on farmers' knowledge can be modelled (Sicat *et al.*, 2005). Livestock grazing distribution mapping has, however, not benefited from these developments. In addition, most of the PGIS projects have not investigated the extent to which the involved local knowledge relates to comparable reference measurements or data, as has been done in other projects (e.g., Li *et al.*, 2004). Classification uncertainty in GIS (as opposed to PGIS) mapping has been addressed in a number of studies (e.g., Dilo *et al.*, 2007; Hope and Hunter, 2007), whereas few PGIS mapping studies that have specifically integrated data on grazing intensity distribution from different information sources (e.g., Van Mourik, 1984; Verweij, 1995) have addressed the problem of representing classification uncertainty.

Traditional methods of verifying participatory data have included implementing different approaches to elicit the same information, referred to as the triangulation or cross-checking technique, using repeated exercises with a representative focus group (Evans *et al.*, 2006; Prins and Wind, 1991; Van der Hoeven *et al.*, 2004). Various mathematical tools are recommended for exploring uncertainty. These include statistical theories, such as Bayesian rules, which are usually applied to deal with stochastic uncertainty (e.g., Cooper, 1992; Evans *et al.*, 2006; Friedman *et al.*, 1997; Ouyang *et al.*, 2006). Systemic uncertainty can be dealt with by using fuzzy sets and fuzzy mathematics through assigning fuzzy membership grades to classes of data with respect to classification criteria (Ding and Kainz, 1998; Zadeh, 1983). In this chapter, we have utilized a related approach that uses evidential belief functions (EBFs) based on Dempster's rule of combination.

Evidential belief functions (EBFs) (Dempster, 1967; Shafer, 1976), which can deal with stochastic and systemic uncertainties together, are finding wider applications to deal with GIS-based classification problems in image analysis (Kim and Swain, 1989; Solaiman *et al.*, 1998; Mertikas and Zervakis, 2001), mineral potential mapping (Moon, 1990; An *et al.*, 1994b; Carranza and Hale, 2002), and natural hazard mapping (Binaghi *et al.*, 1998; Gorsevski *et al.*, 2005; Carranza and Castro, 2006). EBFs are based on the Dempster-Shafer theory of belief (Dempster, 1967; Shafer, 1976) to represent one's subjective perception of a piece of evidence for a particular proposition.

In a PGIS-based project to classify grazing intensity in the study area (Majella National Park, Italy, we encountered the problem of integrating PGIS-based maps of livestock grazing intensity prepared by pastoralists and local rangeland experts (national park staff and researchers), and verifying the reliability of the maps. The grazing intensity classification maps of the study area were produced from separate map-based interviews with the individual participants. The failure to convene a consensus forum to integrate the maps and assess the classification reliability provided the opportunity to test the application of EBFs for PGIS-based map classification uncertainty. Based on selected PGIS-based maps drawn by experts (selection was based on completeness of map classification), the proposition for EBF evaluation was that "*This area or pixel belongs to the high, medium, or low grazing intensity class because the local expert(s) says (say) so*".

We, therefore, investigated (a) the use of PGIS in grazing intensity classification (b) the application of EBFs to represent uncertainty in different PGIS-based maps, (c) how uncertainty in the different PGIS-based maps relates to the criteria used in mapping, (d) the application of Dempster's (1968) rule of combination to synthesize the individual PGIS-based maps into an integrated map of grazing intensity and (e) how grazing distribution based on expert knowledge relates to the grazing suitability index. The relationship was tested using the hypothesis: "a synthesized livestock grazing intensity classification map derived from various groups of local experts correlates well with a grazing intensity classification map derived by integrating landscape-level factors that influence livestock grazing intensity, just as pooled expert products have been used before (Van der Hoeven *et al.*, 2004; Prins and Wind, 1991)".

5.2 Methods

5.2.1 Study area

The study was undertaken in Majella National Park, located in eastern Italy (Chapter 1, Section 1.6).

5.2.2 The PGIS process

The PGIS process involved map-based interviews and group discussions conducted with 20 pastoralists and nine local rangeland experts. Individual or group participants were first interviewed on the management and distribution of livestock grazing. Using the criteria they provided for determining and thus for mapping grazing intensity (e.g., Table 5.1), they were asked to draw the map either by using transparencies on the topographic map or by online digitizing in ARCMAP (ARCGIS 9.1 by ESRI 1999-2005) with a topographic map as backdrop on a laptop computer. Online digitizing allowed interactive participation in attribute data entry and made it possible for the respondents to visualize and connect the responses with the displayed map output. This means that both outputs could be accessed during the production process.

The five maps considered complete for the analysis are used because they depicted all three grazing intensity classes (Figure 5.1). For this study, the consideration of "map completeness" was specifically intended for testing the utility of EBFs for representation of classification uncertainty, for combining the PGIS-based grazing intensity maps into one integrated grazing intensity map and for comparison with a grazing suitability index. The five "complete" PGIS-based grazing intensity maps show different spatial distributions of areas with different grazing intensities (Figure 5.1, Table 5.2). Table 5.3 shows that except for Map2 and Map5, the rest of the maps when compared amongst themselves, significantly differed ($P > 0.001$).

Table 5.1 Criteria used and interpretation by experts in the five PGIS-based maps and the interpretation of the criteria given by the participants. The maps, Map1, Map2, Map3, Map4, and Map5 represent grazing intensity maps drawn by either group or individual participants.

Criteria	Interpretation	Maps
Animal numbers	The higher the numbers, the higher the intensity	Map5, Map3
Altitude	The higher the altitude, the lower the intensity	Map5, Map1
Droppings	The more the droppings, the higher the grazing intensity	Map5
Vegetation species	The higher the composition of palatable species, the higher the intensity	Map4, Map2
Watering points	The nearer the area to watering points, the higher the intensity	Map2

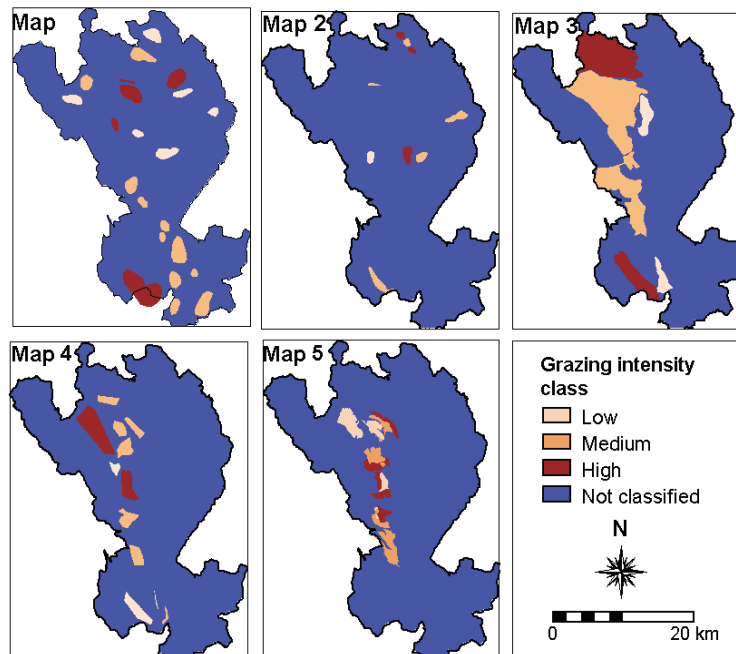


Figure 5.1 Participatory maps: Map1, Map2, Map3, Map4 and Map5 showing variations in the classification of grazing intensity by local experts. The map numbers correspond to those shown in Table 5.1. Grazing intensity classes are: low, medium and high. The blank areas were areas not classified.

Table 5.2 Spatial geo-information for parts of the study area mapped by local experts according to grazing intensity classes. The map codes correspond to those presented in Table 5.1 and Figure 5.1

Grazing intensity	Area (km ²) of mapped grazing intensity class					Percentage (%) of mapped grazing intensity class				
	Map1	Map2	Map3	Map4	Map5	Map1	Map2	Map3	Map4	Map5
High	21.7	4.4	54.4	21.9	13.0	31.2	29.9	34.3	42.4	29.1
Medium	32.9	8.8	91.5	21.8	17.6	47.2	59.9	57.7	42.3	39.4
Low	15.1	1.5	12.8	7.9	14.1	21.7	10.2	8.1	15.4	31.4
Total	69.7	14.7	158.7	51.6	44.7	100.0	100.0	100.0	100.0	100.0

Table 5.3 Correlations amongst participatory maps (1, 2, 3, 4 and 5) in the lower diagonal part of the table. *P*-values for the pairs are indicated in the upper diagonal cells (2,202,776 pixels). The map codes correspond to those presented in Table 5.1 and Figure 5.1

	Map1	Map2	Map3	Map4	Map5
Map1			0.00	0.00	0.00
Map2	-0.51		0.00	0.00	1.00
Map3	0.16	0.33		0.00	0.00
Map4	0.42	0.18	0.36		0.00
Map5	0.15	0.00	0.04	-0.35	

Map3, Map4 and Map5 show that medium to high grazing is concentrated in the central part of the park. Map3 and Map5 were based on animal numbers as common criteria (Table 5.1), whereas Map4 was based on the distribution of palatable vegetation species. Map1 and Map2 show distributions of grazing intensity different from those of Map3, Map4, and Map5. The first two maps were based mainly on altitude and watering points (Table 5.1). In addition, the maps show different areal coverage for each grazing intensity class (Table 5.2). Map3 has the largest land area (158.7 km²) with classified grazing intensities, whereas Map2 has the smallest land area (14.7 km²) with classified grazing intensities. We, therefore, carried out a correlation test (Table 5.3) to confirm these disparities and tested if the disparity in classified land area among the five complete PGIS-based maps may be related with the level of uncertainty as described in the last paragraph of the section (5.2.3) below.

5.2.3 Estimating EBFs for PGIS-based grazing intensity maps

The mathematical formalism of EBFs (Dempster, 1967; Shafer, 1976) is much more complicated than presented in this study. Therefore, the following explanations of EBFs and their utility in the present study are simplified and informal. For a piece of evidence used to evaluate a proposition, three EBFs are estimated for the application of Dempster's (1968) rule of combination (see section 5.2.4 below): *Belief*, *Disbelief* and *Uncertainty*. Each of these EBFs represents the likelihood or probability (i.e., their values are in the range [0, 1]) that a proposition is true or false per given piece of evidence. *Belief* represents the likelihood that the proposition is true based on a given piece of evidence. *Uncertainty* represents the degree of ignorance or doubt that a given piece of evidence supports the proposition.

Disbelief represents the likelihood that the proposition is false based on a given piece of evidence. The sum of *Belief*, *Uncertainty* and *Disbelief* is equal to the maximum likelihood or probability that a proposition is true based on a given piece of evidence (i.e., $Belief + Uncertainty + Disbelief = 1$). *Uncertainty* influences the relation between *Belief* and *Disbelief*. If $Uncertainty=0$ (i.e., there is absolute complete knowledge about a given piece of evidence), then $Belief + Disbelief = 1$ and the relation between *Belief* and *Disbelief* is binary (i.e., $Belief = 1 - Disbelief$ or $Disbelief = 1 - Belief$) as in traditional probability theory. If $Uncertainty=1$ (i.e., there is absolute complete ignorance or incomplete knowledge about a given piece of evidence), then *Belief* and *Disbelief* are both equal to zero. However, it is unusual that one has absolute complete knowledge or absolute complete ignorance about a piece of evidence for a certain proposition, so that usually *Uncertainty* is neither equal to [0] nor equal to [1]. Therefore, in the case that $0 < Uncertainty < 1$, then $Belief = 1 - Disbelief - Uncertainty$ or $Disbelief = 1 - Belief - Uncertainty$. This means that, for a given piece of evidence, the relation between *Belief* and *Disbelief* is usually not binary. Furthermore, this means that, for any piece of evidence used to evaluate a proposition, one should estimate not only *Belief* and *Disbelief* but also *Uncertainty*.

Knowledge-based applications of EBFs, mostly to mineral potential mapping (e.g., An *et al.*, 1992, 1994a, 1994b; Chung and Fabbri 1993; Moon, 1989, 1990; Moon *et al.*, 1991; Likkason *et al.*, 1997; Tangestani and Moore, 2002; Wright and Bonham-Carter, 1996) show the following general estimation procedures. Two of the three EBFs are usually estimated together, and the other EBF is derived based on the relations of the EBFs discussed above. Estimation of *Belief* and *Disbelief* together is usually the most difficult, because one usually tends to think of the binary relation between these two EBFs and thus

neglect estimation of *Uncertainty*. Estimation of *Disbelief* and *Uncertainty* together is also cumbersome, because of one's tendency to be confused between disbelieving and being ignorant about a piece of evidence for a proposition. Estimation of *Belief* and *Uncertainty* together is usually the most convenient, because one usually estimates one's degree of belief in a proposition based on one's degree of knowledge about a given piece of evidence.

From the literature already cited, we further observed the following specific procedures and conditions for estimating *Belief* and *Uncertainty* together. The value of *Belief* is estimated as less than or equal to 0.5 but usually unequal to [0]; meanwhile the value of *Uncertainty* is estimated such that (a) *Belief+Uncertainty* is greater than 0.5 but usually unequal to [1], (b) estimated values of *Belief* and *Uncertainty* are inversely proportional, and (c) derived values of *Disbelief* (i.e., $1 - \text{Belief} - \text{Uncertainty}$) are inversely proportional to estimated values of *Belief*. The value of *Belief* is usually kept asymptotic or unequal to [0], whereas the sum of *Belief+Uncertainty* is usually kept asymptotic or unequal to [1] because, as stated earlier, it is unusual that one has absolute complete knowledge or absolute complete ignorance about a piece of evidence for a certain proposition. Thus, *Uncertainty* is usually estimated as unequal to [0] or unequal to [1], and thus either *Belief* or *Disbelief* is usually estimated as unequal to [0]. Estimations of *Belief=0* and *Uncertainty=1* are appropriate, however, if, and only if, there is complete ignorance about a piece of evidence in relation to a proposition. In this case, the aforesaid conditions for estimating *Belief* and *Uncertainty* together do not apply.

To synthesize the five complete PGIS-based grazing intensity maps into an integrated grazing intensity map via applications of EBFs, we used each of the five complete PGIS-based grazing intensity maps as an individual set of spatial evidence. Based on the aforesaid procedures and assumptions for estimating EBFs, we estimated *Belief* and *Uncertainty* together (Table 5.5) for each grazing intensity class (low, medium, high) according to the proposition "This area or pixel belongs to the high, medium, or low grazing intensity class because the local expert(s) says (say) so". For the "high" grazing intensity class, we estimated the highest *Belief* and the lowest *Uncertainty* because each of the local experts' classifications of areas as high grazing intensity was considered to be based on their best knowledge and least ignorance of such areas. For the "medium" and "low" grazing intensity classes, we estimated decreasing values for *Belief* and increasing values for *Uncertainty* at equal intervals, because (a) each of the local experts' classifications of areas as medium or low

grazing intensity was considered to be based on their decreasing knowledge and increasing ignorance of such areas, and (b) we assume that the local experts think of linear (e.g., equal-interval) classification scales as used in other map classification problems (e.g., Clomley, 1996; Leung et al., 2007). For areas whose grazing intensity was not classified by the local experts (Figure 5.1), we estimated *Belief* to be minimum (=0) and *Uncertainty* to be maximum (=1). After having estimated *Belief* and *Uncertainty* for each grazing intensity class, we derived *Disbelief* as equal to $1 - \text{Belief} - \text{Uncertainty}$ (Table 5.5).

According to the explanations regarding the estimation of EBFs above, the local experts' grazing intensity classifications can be represented by different sets of EBFs, because different analysts may have different perceptions concerning a piece of evidence for a proposition and thus give different sets of EBF estimates. To verify which of the two sets of estimated/derived EBFs adequately represents classification uncertainty, we calculated the class-area-weighted averages of EBFs per grazing intensity class per map. To do so, we multiplied the estimated EBFs per class (Table 5.5) to the corresponding class area (Table 5.2) and then divided the product by the sum of the areas of all classes. Note that the class-area-weighted average of EBFs is algebraically equal to the product of the estimated EBF per class and the corresponding class area percentage (Table 5.2). We used the class-area-weighted average of EBFs to verify whether the estimates of EBFs were realistic, because the local experts were considered to have applied the mapping criteria (Table 5.1) in a spatial context (i.e., areal) when they delineated the boundaries of certain areas according to their local spatial knowledge of grazing intensities.

5.2.4 Applying Dempster's rule of combination to integrate the five maps

The estimated and derived EBFs for each of the five PGIS-based grazing intensity maps were stored in their associated attribute tables (within a GIS). We then created attribute maps of *Belief*, *Disbelief* and *Uncertainty* associated with each grazing intensity map, and used Dempster's (1968) rule of combination to integrate the different EBF maps.

According to Dempster's (1968) rule of combination, only EBFs of two pieces of evidence can be combined each time. It means that if, for example, there are three pieces of evidence (E_1, E_2, E_3), EBFs for evidence E_1 are combined first with EBFs for evidence E_2 in order to obtain partial integrated EBFs for pieces of evidence E_1 and E_2 . The

EBFs for evidence E_3 can then be combined with the partial integrated EBFs for E_1 and E_2 in order to obtain final integrated EBFs for all the three pieces of evidence. Note, however, that equations for combining the EBFs of several pieces of evidence according to Dempster's rule are both commutative and associative (see below). Therefore, different groupings or sequences of evidence combinations do not affect the final result.

Dempster's rule of combination is implemented by using arithmetic operations that are equivalents of logical operations used in the application of classical set theory. In the present study, we applied the OR operation (equivalent to the UNION operation) for combining pieces of evidence because it is suitable when at most one piece of evidence has to be present in order to consider the proposition to be true. In this study, the application of the OR operation implies that, for example, if an area is classified by one local expert as high grazing but by another as low grazing, then grazing intensity in such an area ranges between low and high. The equations for combining the EBFs of two pieces of evidence via the OR operation are as follows:

$$Bel_{E_1E_2} = \frac{(Bel_{E_1}Bel_{E_2} + Bel_{E_1}Unc_{E_2} + Bel_{E_2}Unc_{E_1})}{1 - Bel_{E_1}Dis_{E_2} - Dis_{E_1}Bel_{E_2}} \quad (\text{Eq. 5.1})$$

$$Dis_{E_1E_2} = \frac{(Dis_{E_1}Dis_{E_2} + Dis_{E_1}Unc_{E_2} + Dis_{E_2}Unc_{E_1})}{1 - Bel_{E_1}Dis_{E_2} - Dis_{E_1}Bel_{E_2}} \quad (\text{Eq. 5.2})$$

$$Unc_{E_1E_2} = \frac{(Unc_{E_2}Unc_{E_1})}{1 - Bel_{E_1}Dis_{E_2} - Dis_{E_1}Bel_{E_2}} \quad (\text{Eq. 5.3})$$

where *Bel*, *Dis* and *Unc* are, respectively, *Belief*, *Disbelief* and *Uncertainty*, and E_1 and E_2 are two pieces of evidence (e.g., Map1 and Map2 in Table 5.1). Note that all equations (Eq. 5.1, Eq. 5.2 and Eq. 5.3) have the same denominator. This constant denominator represents the total likelihood or probability, in the range [0,1], that a proposition is true based on two contradictory pieces of evidence (Kim and Swain, 1989). If the term $Bel_{E_1}Dis_{E_2} - Dis_{E_1}Bel_{E_2}$ in the constant denominator is equal to [1], then it means that two pieces of evidence are completely contradictory, such that the assumption that the orthogonal sum $Belief + Uncertainty + Disbelief = 1$ is not valid, and thus the integrated EBFs are meaningless. The constant denominator in all the equations given above also serves to normalize the integrated EBFs in the range [0,1] so that the relation $Belief + Uncertainty + Disbelief = 1$ is maintained.

The probabilities (Table 5.5) were applied to the five grazing intensity maps. In each map, there was already a column containing grazing intensity class as "gi_class". Thus, assuming Eq. 5.4, for each of the five maps *Belief*, *Uncertainty* and *Disbelief* values were derived per intensity class by using Eqs. 5.5 to 5.7 below:

$$Bel + Unc + Dis = 1 \quad (\text{Eq. 5.4})$$

$$Bel = \text{iff}(\text{gi_class}=3, 0.5, \text{iff}(\text{gi_class}=2, 0.3, 0.1)) \quad (\text{Eq. 5.5})$$

$$Unc = \text{iff}(\text{gi_class}=3, 0.4, \text{iff}(\text{gi_class}=2, 0.45, 0.5)) \quad (\text{Eq. 5.6})$$

$$Dis = 1 - bel - unc \quad (\text{Eq. 5.7})$$

In stepwise combinations of two maps at a time, each set of the five expert-based grazing intensity maps (Figures 5.4, 5.5. and 5.6) were combined into one, using Eqs. 5.5, 5.6, and 5.7 for *Belief*, *Disbelief* and *Uncertainty*, respectively. This resulted in maps comprising integrated *Belief*, integrated *Disbelief*, and integrated *Uncertainty* (Figure 5.7).

5.2.5 The SMCE process

The SMCE process comprised two main steps: the selection of landscape factors (also referred to as criteria) that influence livestock grazing distribution, and the evaluation and integration of the selected criteria into a "composite index map" (livestock grazing suitability index map). The process was carried out by a group of independent researchers, including one short-term researcher at Majella National Park (not included in the mentioned Majella National Park experts).

Three factors, vegetation structure (life forms), terrain and park management zoning, were used. From the factors mentioned in section 5.1, we focused on vegetation and terrain, and land use (park zoning). Terrain and vegetation were selected based on general location conditions for extensive livestock, including grazing behaviour and rangeland evaluation factors (Stuth, 1991; Van Gils, 1984). Terrain was considered as a limiting factor for livestock accessibility since Majella National Park is mountainous. The park management zonation factor is relevant because of conservation-oriented planning, land allocation policy, and socio-political context as used by Van Mourik (1984). We limited the criteria to only three in order to keep the index simple. Figures 5.2a and 5.2b show the maps of the factors and their attributes, while Table 5.4 shows the criteria weights and evaluation scores. The maps and literature were obtained from the Majella National Park office. Modifications included

reclassification of the 1999 vegetation map in order to reduce the number of classes for ease of analysis, while the terrain map was derived from an existing digital elevation model and a topographic map. An extended legend of the vegetation map (Figure 5.2a) was, unfortunately, not available. The selected criterion maps are elaborated below.

5.2.5.1 Vegetation and terrain

The vegetation is described according to structure (life forms) at community level, together with associated terrain (Figure 5.2a). The vegetation of Majella comprises mostly Mediterranean scrub and garigue (high shrubby scrub), commonly dense and impenetrable, and highly heterogeneous (Jones, 2000). Twisted shrubs are limited to altitudes of 1800 m owing to rampant clearing for livestock pasture. The area presently includes pinewood, mainly *Pinus mugo*, interspersed with creepers, *Arctostaphylos uvaursi* and *Juniperus communis* subsp. *communis*. Shrubs undesirable for livestock grazing, such as *Juniperus sabina* (known to have abortive properties), have been destroyed by shepherds to give way to pastures. The rock pastures contain pioneer species such as *Festuca dimorpha*. These pastures are called secondary because they come from a long process of clearing for livestock pastures. They are usually colonized in successive phases by *Juniperus communis* subsp. *communis* or other plants not eaten by livestock, such as *Carlina acualis*, *Carlina acanthifolia* and *Cynoglossum appenninum*.

Beech (*Fagus sylvatica*) forest covers an area of altitude between 1000 and 1800 m, and the forest comprises beech with arboreal undergrowth. At the edges of the beech forest and in the clearing are *Laburnum anagyroides* and small fruit-bearing shrubs such as *Rubus ideaus*. The *Quercus cerris* forest follows in altitude at 500 and 1200 m and covers parts of the southern parts of the park. These forests are interspersed with other species such as *Prunus mahaleb*, shrubs, and the undergrowth of climbing plants. The oak groves were used in the Middle Ages for pasture in autumn but are now inhabited mainly by wild boar, ibex, red deer, brown bear, roedeer, etc. *Fraxinus ornus* and *Ostrya carpinifolia* woods and some shrubs dominate the calcareous sides of the mountain. Medium altitudes are represented by arctic–alpine species, such as *Dryas octopetalus*, *Saxifraga oppositifolia*, *Gentiana dinarica* and *Paronichia kapela*.

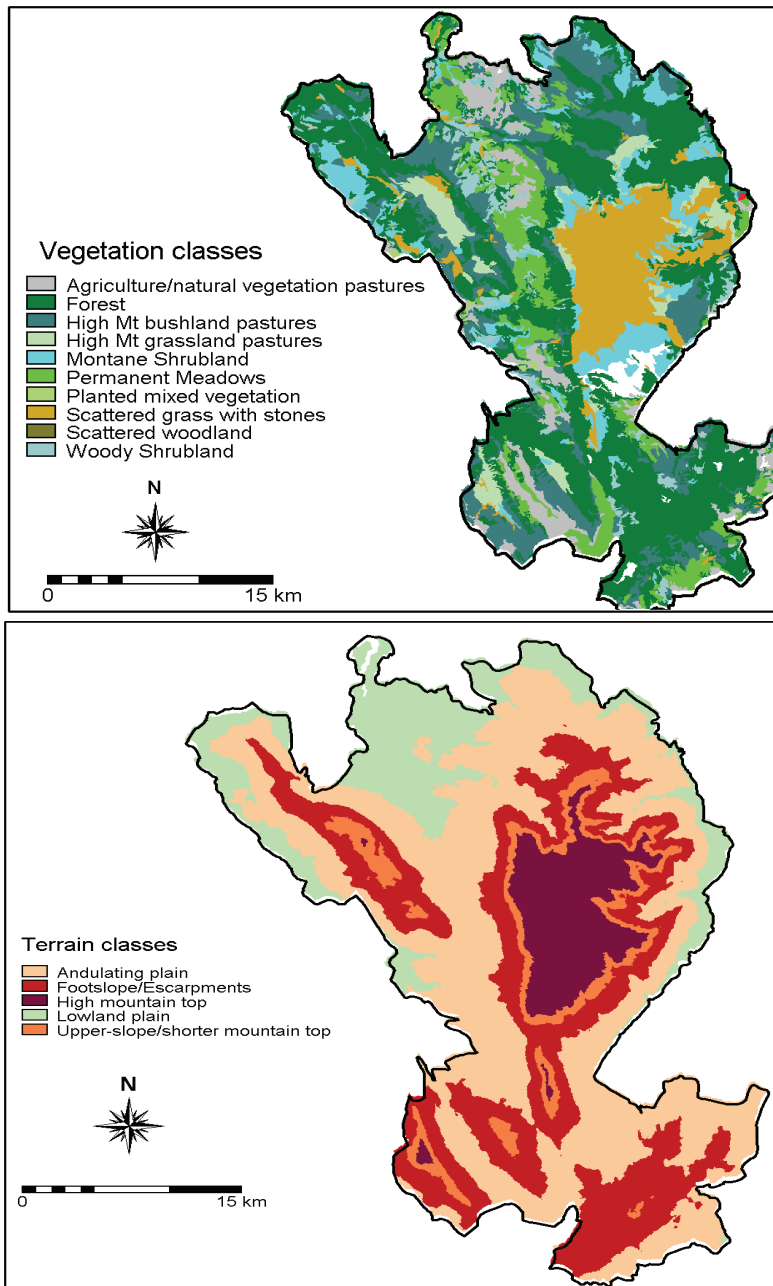


Figure 5.2a Vegetation map (upper) and Terrain map (Lower) of Majella National Park: two of the factors (criteria) used in the SMCE for evaluating livestock grazing suitability.

According to the information obtained from local pastoralists and local experts, the grass and herb species of preference to livestock grazing are mostly located in the lowlands, undulating plains and foothills. The species mentioned included *Trifolium spp*, *Vita alba*, *Lotus corniculatus*, *Festuca spp*, *Thymus spp*, *Medicago sativa*, *Carrota spp.*, *Clematis spp*, *Dactylis glomerata*, *Bromus erectus*, *Cathyrus cicera*, *Sumbucus spp*, *Rosa canina*, *Urtica spp*, *Lolium perenne*, and *Lolium multiflorum*.

5.2.5.2 National park management zoning

Pastoralism and other activities are still accommodated in Majella National Park, but park management zoning limits their spatial distribution. A national park, by the IUCN definition, is an area managed mainly for ecosystem protection, recreation, and the protection of ecological integrity. The rethinking of this policy has seen a modification to more cultural-indigenous-based management, making it possible for the maintenance of anthropological zones (Eilers, 1985:7, in Stevens, 1997). Pastoralism is one of the activities that may be considered in a national park where other objectives such as recreation and conservation influence the allocation of grazing areas. The management zoning map of Majella National Park (1999), (Figure 5.2b) was therefore considered in the spatial factors that influence livestock grazing distribution.

The zones are listed here according to protection level (i.e., from the most protected to the least) within the park area:

- Total protection: Economic and human activities are strictly not permitted;
- General reserve: Economic activities are still not allowed; it is possible to restore old traditional buildings/houses but it is not possible to build new houses or infrastructure (only the Park Board can do this);
- Area of some (limited) protection: Some economic activities are allowed on a small scale, such as organic (biological) agriculture and livestock keeping and traditional artisan activity;
- Small villages under the administration of the Commune; and
- Tourist infrastructure that needs to be reorganized (rehabilitation and restoration).

To perform the spatial multicriteria evaluation (SMCE), tool within a GIS (ILWIS Academic, developed at ITC, Enschede, the Netherlands) was used. This application guides a decision maker through an automated SMCE process. It takes multiple spatial layers of maps (referred to as criteria or effects) and provides options for structuring

and grouping, standardizing, weighing, constraining, and combining them into one or more composite index maps. These are maps that indicate the extent to which criteria are met or not in different areas (Sharifi and Retsios, 2004).

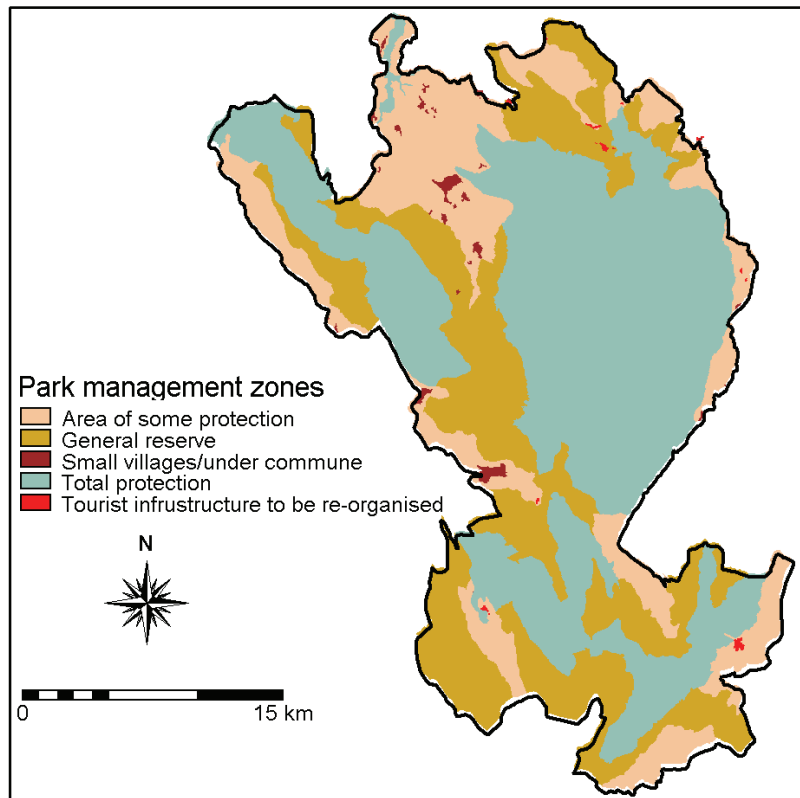


Figure 5.2b Map of Majella National Park showing management zones of 1999: the third factor (criteria) used in the SMCE for evaluating livestock grazing suitability.

The combination model that we used for the three criteria (vegetation types, terrain and park zonation) was based on a premise that "a high (partial) suitability for grazing for any of these criteria will result in a higher total suitability for grazing in that area". Because this is a small number of criteria, the model we used utilised a simple structure. The simplest structure was used, where the criteria are first standardized and then combined by a weighted linear combination (Malczewski, 1999).

In order to enable criteria comparisons, each of the criteria maps was standardized, i.e., converted to a common unit. In the SMCE

application, this unit comprises floating point values between 0 and 1, where 0 assignment means unsuitable for the objective set (in our case livestock grazing), and 1 is very suitable. The SMCE application provides three methods for doing this: directly entering the value that corresponds to a class; the analytic hierarchy process (AHP), which uses pair-wise comparison (Saaty, 1980); and rank ordering. For all three criteria, the rank-ordering method was used. This method is relatively simple and ensures better consistency than directly entering values. The rank-ordering process was implemented using the SMCE application in ILWIS GIS. The classes for each criterion were ranked from "most suitable for grazing" to "least suitable for grazing". Through the SMCE tool, the "expected value" formula was executed in order to generate standardized values between 0 and 1 for each class. Table 5.4 shows the standardized values for the classes of each criterion in the column named "Score". Some values are equal because the rank position of the corresponding items was the same. For brevity, the maps showing the standardized values are not presented.

For comparing the criteria and deciding their relative influence on the grazing suitability of an area, their weights were allocated and assessed. The SMCE application was used in assessing weights within the hierarchical structure of the criteria. The weight assessment method selected in this case was the AHP. The AHP process derives a priority vector from relative weights for the elements (the principal eigenvector of the matrix) of the given criteria. Details of similar calculations are available in Sharifi and Retsios (2004). The AHP method was used instead of other weighting methods (rank ordering, direct weighing) because it ensures the highest consistency of the evaluation process. The disadvantage of the AHP process is that it is only suitable for a small number of criteria, because when the number of items to be compared becomes large, too many comparisons have to be made. In our case the number of criteria was only three and not amenable to this problem. Using the AHP function within the SMCE application in ILWIS GIS, the pair-wise comparison was executed resulting in the criterion weights shown in Table 5.4 ("Criterion/weight" column).

Finally, the criterion weights were used in the following SMCE application formula for calculating the suitability map:

$$\text{Suitability} = 0.69 * \text{Vegetation} + 0.08 * \text{Terrain} + 0.23 * \text{Park_zonation} \quad (\text{Eq. 5.8})$$

where *Vegetation*, *Terrain* and *Park_zonation* represent the standardized version of the corresponding criterion maps.

This formula (Eq. 5.8) is executed repeatedly for each pixel in the maps until the entire suitability map is calculated.

Table 5.4 SMCE criteria, relative weights and standardized suitability scores

<i>Criterion/ weight</i>	<i>Attributes</i>	<i>Suitability class</i>	<i>Score</i>
Vegetation (0.69)	Montane shrubland	Medium	0.54
	Forest	Low	0.18
	High mountain shrubland pastures	Medium	0.54
	High mountain grassland pastures	High	1.00
	Permanent meadows	High	1.00
	Agriculture and natural vegetation	Low	0.18
	Scattered grass with stones	Low	0.18
	Woody shrubland	Low	0.18
	Planted mixed vegetation	Low	0.18
	Scattered woodland	Low	0.18
	Very sparse high mt. vegetation	Low	0.18
Terrain (0.08)	Lowland plain	High	1.00
	Undulating plain	High	1.00
	Footslope/escarpment	Medium	0.35
	Upper slope/low mountain top	Medium	0.35
	High mountain top	Low	0.11
Park zonation (0.23)	Total protection	Low	0.21
	General reserve	High	1.00
	Area of protection	Medium	0.56
	Small villages under the Commune	Low	0.21
	Tourist infrastructures	Low	0.21

5.2.6 Comparison of grazing intensity classification map and grazing suitability index

The relationship between the grazing intensity map and the grazing suitability index map (Figure 5.8) was established through statistical comparisons. First we used descriptive statistics to explore the distribution of the data. A Pearson correlation test was used to establish the extent to which the two maps related. Visual comparisons were also made.

5.3 Results

5.3.1 Representation of uncertainty in the five PGIS-based grazing intensity maps

Table 5.5 shows the two sets of EBFs that were estimated and investigated. The values for *Belief* in both sets are equal, but set 1 has higher values for *Uncertainty* than set 2. Consequently, set 1 has lower values for *Disbelief* than set 2. In any set of estimated EBFs, *Belief*=0 and *Uncertainty*=1 were assigned to "unclassified" areas to portray the local experts' lack of knowledge of such areas with respect to the classification criteria for grazing intensity (Table 5.1). The disparity in classified land area among the five complete PGIS-based maps (Table 5.2) may seem to indicate that Map2 has the highest classification uncertainty. This is not so, however, as shown in the verification of estimated EBFs for each grazing intensity class; rather it is the percentage of land per grazing intensity class that is more or less related to the degree of classification uncertainty per map. For example, 10.2% of total classified land in Map2 is mapped as low grazing intensity, whereas 31.4% of total classified land in Map5 is mapped as low grazing intensity. As shown further below, Map5 has higher classification uncertainty than Map2.

The results of our verifications regarding which of the two sets of estimated/derived EBFs adequately represents classification uncertainty show that, for each of the two sets of estimated/derived EBFs (Table 5.5), the class-area-weighted averages of EBFs per map differ mainly with respect to *Uncertainty* and *Disbelief* (Figure 5.3). The estimated/derived EBFs in set 1 result in a different class-area-weighted average for *Uncertainty* per map, whereas the estimated/derived EBFs in set 2 result in an almost equal class-area-weighted average for *Uncertainty* per map. For the estimated EBFs in set 1 (Table 5.5), the variations in class-area-weighted average for *Uncertainty* (Figure 5.3) show good correlation with the variations in the percentage of the low grazing intensity class (Table 5.2), which probably depicts the highest uncertainty among the three classes of grazing intensity.

These results indicate that the estimated/derived EBFs in set 1 are more realistic representations of classification uncertainty per map than the estimated/derived EBFs in set 2, because the individual participants were considered to have different perceptions of the grazing intensities in the study area since they independently assessed and mapped using different mapping criteria. In comparison with all the other sets of EBFs that we estimated (not shown here because of space limitations), we considered the estimated EBFs in

set 1 (Table 5.5) to be the most adequate representation of classification uncertainty in each of the five complete PGIS-based grazing intensity maps. The values for *Belief*, *Uncertainty* and *Disbelief* per grazing intensity map are shown in Figures 5.4, 5.5 and 5.6, respectively.

Table 5.5 Sets of estimated and derived Evidential Belief functions for each grazing intensity class.

Set	Grazing intensity class	Estimated EBFs		Derived EBF
		Belief	Uncertainty	Disbelief
1	Low	0.16	0.75	0.09
	Medium	0.33	0.60	0.07
	High	0.50	0.45	0.05
	Unclassified	0.00	1.00	0.00
2	Low	0.16	0.50	0.34
	Medium	0.33	0.45	0.22
	High	0.50	0.40	0.10
	Unclassified	0.00	1.00	0.00

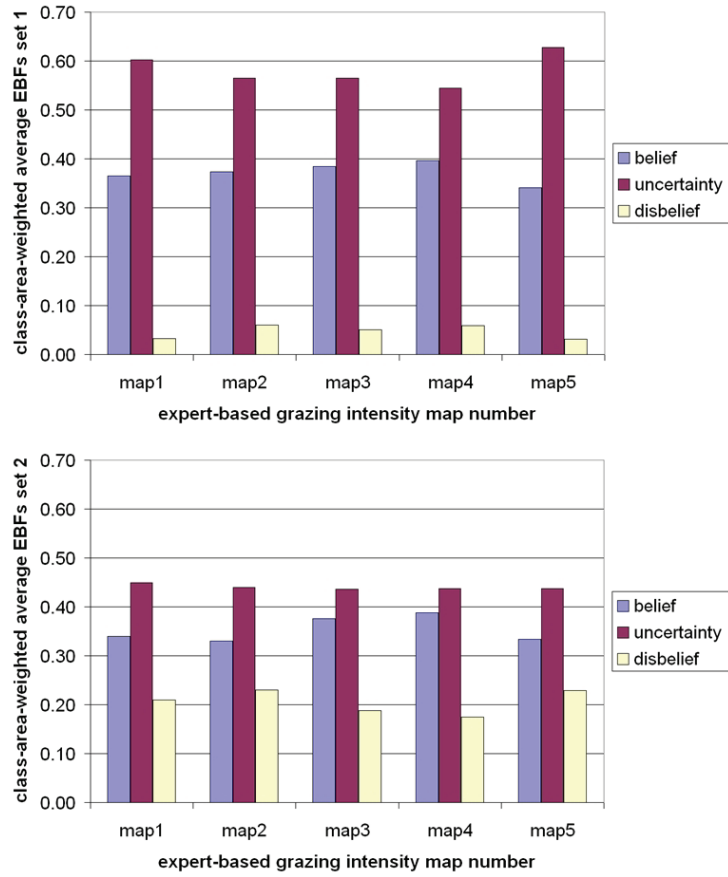


Figure 5.3 The two alternative estimated/derived EBFs: set 1 (top) and set 2 (bottom) showing class-area-weighted averages for EBFs per map.

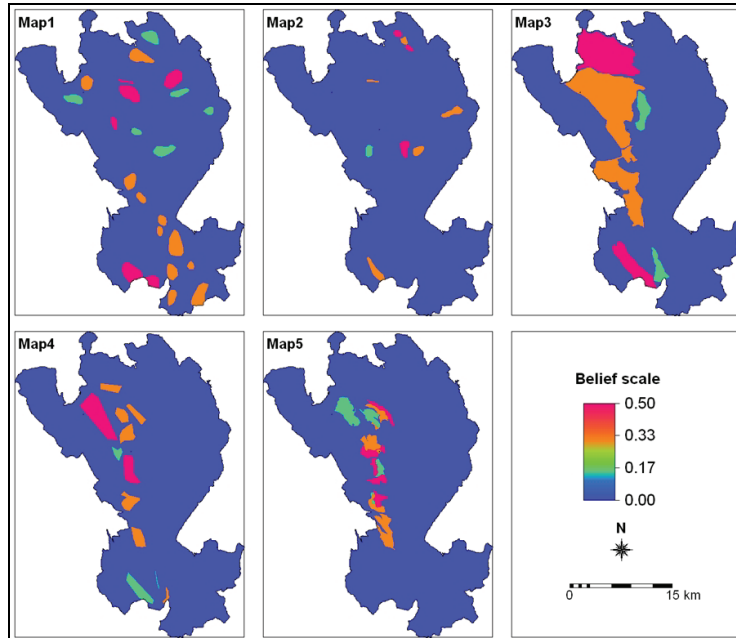


Figure 5.4 Belief values in local experts' grazing intensity classifications

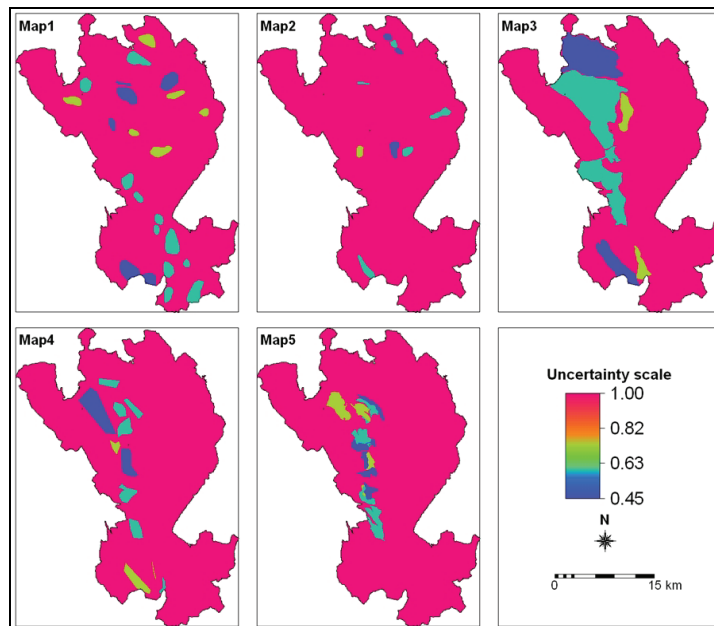


Figure 5.5 Uncertainty values in local experts' grazing intensity classifications

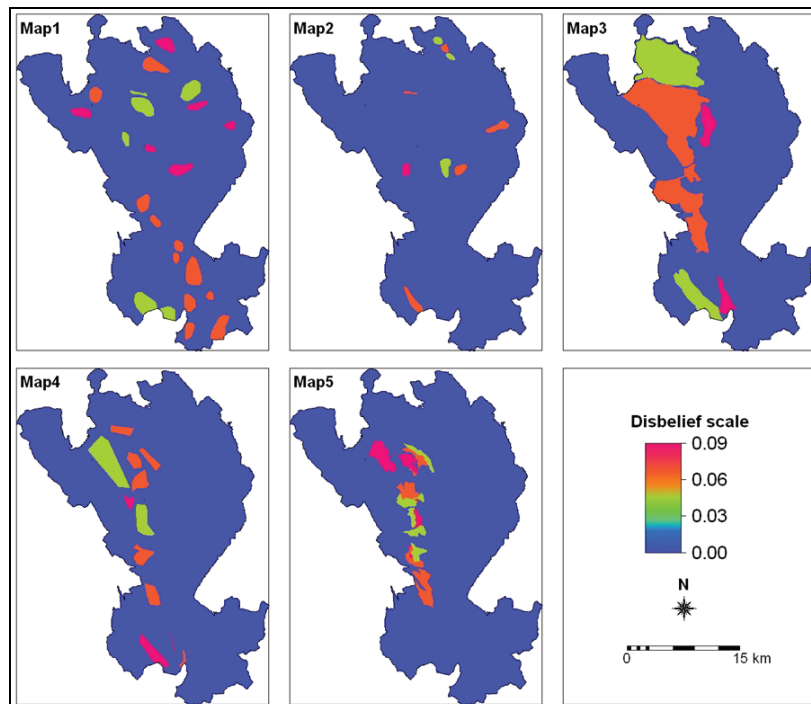


Figure 5.6 *Disbelief* values in local experts' grazing intensity classifications

5.3.2 Uncertainty in the PGIS maps versus criteria used

The variations in the class-area-weighted averages of EBFs for set 1 (Figure 5.3, upper graph) may be explained by, and thus related to differences in the type and number of mapping criteria used by the local experts (Table 5.1). For example, Map2 and Map4 have lower *Uncertainty* than Map1 and Map5 (Figure 5.3, upper graph), probably because the distribution of palatable vegetation species is a better criterion for grazing intensity than altitude. In addition, Map4 has lower *Uncertainty* than Map2 and Map5 (Figure 5.3, upper graph), probably because the local experts are less confused when using one criterion (Map4) than when using at least two criteria (Map2, Map5).

5.3.3 Integrated EBFs of grazing intensity

Figure 5.7 shows the maps of integrated *Belief*, integrated *Disbelief*, and integrated *Uncertainty* in grazing intensity in the study area. The maps of integrated EBFs are in accord with the relations of EBFs discussed in section 5.2.3. The integrated values of *Belief* are inversely proportional to the integrated values of *Uncertainty* and integrated values of *Disbelief*, except in areas where there is complete *Uncertainty*. The maps of integrated EBFs show the

distribution of grazing lands mostly in the north-south central valley and plains. A similar pattern of grazing land distribution can be identified in three maps (Map3, Map4, Map5) of the original five complete PGIS-based maps (Figure 5.1). The similar patterns of grazing land distributions in most of the PGIS-based grazing intensity maps (also shown by correlation results for Map2 and Map5 in Table 5.3) and the maps of integrated EBFs of grazing intensity indicate a common understanding of the grazing system by the different groups of local experts.

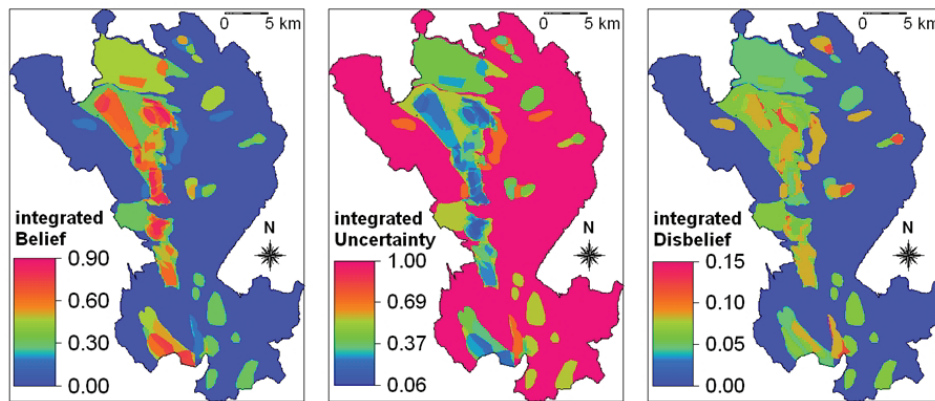


Figure 5.7 Maps of integrated *Belief* (A) integrated *Disbelief* (B) and integrated *Uncertainty* (C) in local experts' grazing intensity classification

5.3.4 Relations between grazing intensity classification and grazing suitability index

Figure 5.9 below shows that the mean of the grazing intensity index decreases with grazing intensity class. Therefore, as expected, the higher the grazing suitability index, the higher the grazing intensity class. This can also be reflected in the visual comparisons of the maps in Figure 5.8. The grazing intensity classification of extreme classes (i.e., high and low) is highly variable compared with that of the medium class (Figures 5.9a and 5.9b).

The calculated Pearson correlation coefficient between grazing suitability index and grazing intensity maps integrated using EBFs was found to be 0.35 ($p < 0.01$). This implies a weak correlation between grazing intensity classification by local experts and landscape factors influencing grazing distribution that were identified by the researchers.

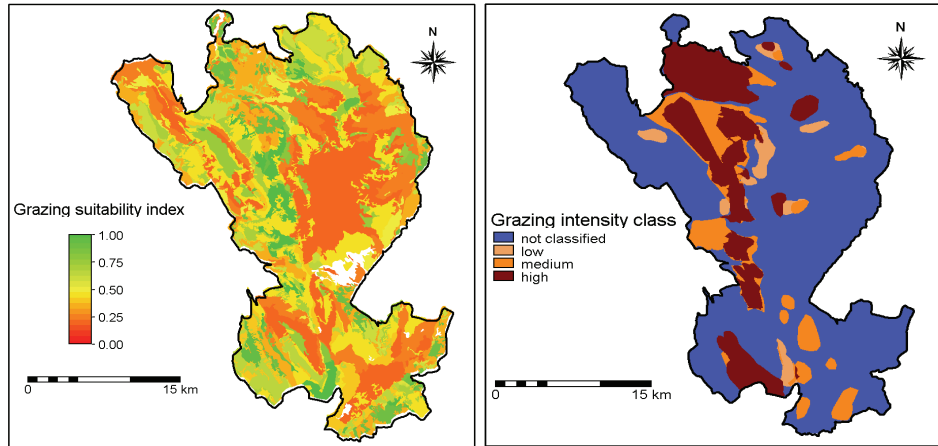


Figure 5.8 Grazing suitability index (left) and integrated grazing intensity map (right)

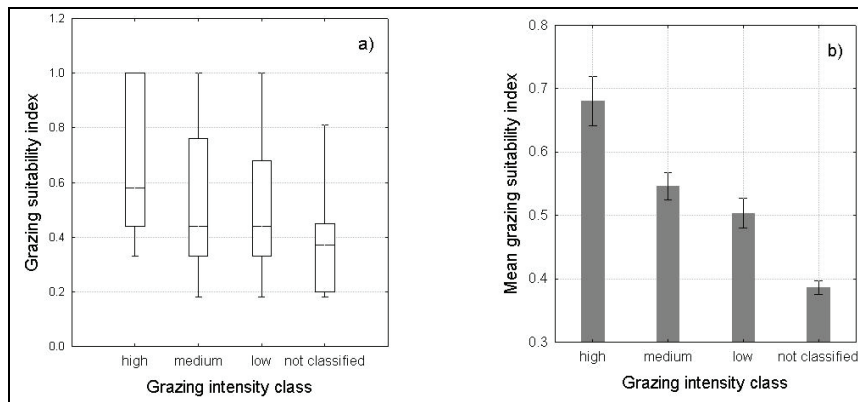


Figure 5.9 (a) Box plot showing the variability in the dataset, and (b) mean values of grazing suitability index within each grazing intensity class. Vertical bars (whiskers) in (b) denote 0.95 confidence intervals.

5.4 Discussion

In this chapter, we have demonstrated (a) the use of PGIS in grazing intensity classification (b) the application of EBFs to represent uncertainty in different PGIS-based maps, (c) how uncertainty in the different PGIS-based maps relates to the criteria used in mapping, (d) the application of Dempster’s (1968) rule of combination to synthesize the individual PGIS-based maps into an integrated map of

grazing intensity and (e) how grazing distribution based on expert knowledge relates to the grazing suitability index.

In contrast to the view that the use of local knowledge is limited in spatial analysis (e.g., Brouwers, 1993; Jansen, 1998), the use of PGIS helped to:

- elicit spatial knowledge both in attribute and map format as a vital contribution to mapping and analysis of grazing intensity;
- generate relevant criteria for classifying grazing intensity;

Moreover,

- participants who had not drawn maps before understood the decision-making process involved in classifying their landscape through connecting criteria with map drawing; and
- interactive visualization between interview data and map attribute spatial data in a GIS was possible.

This does not preclude the limitations encountered in the PGIS process. Although the pastoralists showed more understanding of grazing management aspects and species preferred by livestock (Bemigisha *et al.*, in preparation), they could not easily represent this knowledge on a map. The minimal concentration on the map drawing because of the day-long movement of the shepherds, as well as failure on the part of the authors to convene a consensus forum, may have affected the development and application of criteria by the pastoralists. The study shows that a different PGIS tailored to pastoralism may be needed. Other studies (e.g., Tripathi and Bhattarya, 2004) show that such limitations can be handled. The advantage of interviews with individuals, however, was that individual original knowledge was captured without group coercion and intimidation.

The limitations in this study, specifically, the difficulties in convening a consensus forum for the final map making provided an opportunity to investigate the integration of the participatory maps and explore representation of classification uncertainty.

Using EBFs to evaluate uncertainty, we found that class-area-weighted averages of EBF values can be related to the mapping criteria used. The participants used spatial characteristics based on their understanding of the factors that influence or constrain grazing distribution as criteria for drawing the maps. According to the class-area-weighted EBF values, Map2 and Map4 showed lower *Uncertainty* than Map1 and Map5. Since the maps that showed the lowest uncertainty were based on the distribution of palatable vegetation

species, we concluded that this criterion is a better parameter for mapping grazing intensity than, for example, altitude, which was used in Map1 and Map5. The distribution of vegetation species as a criterion, however, does not fully define a grazing intensity class, as defined by Bakker (1989). His definition includes forage condition measured against a livestock utilization factor.

Thus, if we consider the direct visually observed impacts of livestock foraging, and resting on vegetation attributes, the appropriate proposition may be defined as: "*This pixel or area is a specific grazing intensity class because of the level of livestock grazing use and its impacts on vegetation attributes*". These attributes may include ground cover (proportion), quantity and quality (e.g., Skidmore *et al.*, 2005). Future research should therefore investigate how local pastoralists and experts can be guided to investigate and apply EBFs based on such a proposition.

The results also indicate that the EBFs could be related to the number of criteria used. This is shown by Map4, with lower *Uncertainty* than Map2 and Map5, suggesting that the local experts were less confused when using one criterion (Map4) than when using at least two criteria (Map2, Map5). The challenge of analyzing multiple criteria has been observed by other authors (e.g., Jansen, 1998). Solutions to these problems are found in spatial multicriteria evaluation (SMCE) tools (Malczewski, 1999).

The application of EBFs to the five different PGIS-based grazing intensity maps was based on the proposition that "*This area or pixel belongs to the high, medium, or low grazing intensity class because the local expert(s) says (say) so*". We found variations in the class-area-weighted average for *Uncertainty* per map when the interval between the values for *Uncertainty* per class was increased (Table 5.5, Figure 5.3). On the one hand, this means that there are variations in knowledge among the groups of local experts who created each grazing intensity classification map. This variation was also revealed in the correlation amongst the grazing intensity maps (Table 5.2). On the other hand, the variations in the class-area-weighted average for *Uncertainty* per map could probably have been influenced by the type and number of mapping criteria used by the individuals or groups to classify grazing intensity. Sicat *et al.* (2005) established that individual farmers' perceptions regarding the classification of land suitability based on a combination of different factors (criteria) can be organized using fuzzy modelling, but the fuzzy knowledge rules involved have to be built into the initial mapping stages. This was not the case in this study.

Estimating fuzzy membership scores is difficult and may be more challenging than the application of EBFs. In EBF modelling at least two values are considered - one representing the variable of interest (e.g., grazing intensity) and another representing classification uncertainty - whereas in fuzzy modelling only one value (fuzzy membership score) - representing both the variable of interest and uncertainty - is considered. This study demonstrates that estimating *Belief* and *Uncertainty* interactively is not easy - as shown, for example, by the different sets of EBF values that can be obtained from the same evidence (Table 5.5). Therefore, PGIS-based classification projects need to investigate how EBFs and fuzzy theory may be implemented with diverse local participants.

Applying Dempster's rule of combination to integrate the five maps resulted in grazing intensity maps with integrated *Belief*, *Disbelief* and *Uncertainty*, which is a new development in PGIS and livestock distribution mapping. Classification is not considered complete, however, unless the product has been validated (Lillesand *et al.*, 2004; Kerle *et al.*, 2004). Therefore, beyond the establishment of uncertainty and the integration of different maps, further investigation is needed to establish a classification system for grazing intensity and, based on this classification system, a validation system for PGIS-based grazing intensity maps.

Similar patterns of grazing distribution in the central valley and northern and southern plains suggest a close spatial relationship, indicating a degree of common understanding of the system by the different participants. This means that the criteria used by the different participants highlight relationships where spatial-data-driven EBFs are possible in a PGIS process. In a study related to scaling degradation levels using data-driven EBFs, Thiam (2005) found that spatial variations were adequate support for given evidence. Areas of high probability for degradation coincided with human artifacts such as settlements, boreholes and roads. Independent expert opinions from the domain of natural resources sciences have also been integrated, using the Delphi approach (e.g., Prins and Wind, 1991; Van der Hoeven *et al.*, 2004). The Delphi technique is based on consensus obtained from the opinions of experts, without necessarily bringing them together in a single forum as done in this study. There is, however, need to evaluate the utility of this technique against "good PGIS practice", especially regarding group dynamics and consensus. Carranza *et al.* (2005) recommend as the ideal situation one in which expert opinion can be added to authenticate already known occurrences within data-driven EBFs. It may therefore be

possible in future to apply both knowledge and data-driven EBFs in mapping that involves PGIS.

To test the relationship between a grazing distribution map and a grazing suitability index, the hypothesis was that the livestock grazing intensity classification map derived from various groups of local experts correlates with a grazing intensity classification map derived by integrating landscape-level factors that influence livestock grazing intensity. Our findings show that the higher the grazing intensity, the higher the grazing suitability index (Figure 5.8), indicating that the two maps were related. Other studies (e.g., Sicat *et al.* 2005) have found maps resulting from scientific land suitability classification consistent with farmer's knowledge on rules of classification. Consistency has been found between farmers' and scientific attributes (e.g., Agrawal, 1995; Soto-Pinto *et al.*, 2007). The Pearson correlation test for our study, however, showed the coefficient between the grazing suitability index and the grazing intensity map as 0.35 ($P < 0.01$), implying a weak correlation.

The weak correlation between the grazing suitability index and the grazing intensity map suggests that grazing may be largely distributed where it is not suitable. The weak correlation could also have been due to limitations in the expert knowledge and the SMCE criteria selection and evaluation. The suitability index could have benefited from more spatial factors and participation of the local experts and pastoralists. Moreover, the subjective ranking of criteria in the SMCE process generates its own uncertainty (e.g., Smith *et al.*, 2006; Van der Lee *et al.*, 2006), that should be a subject of further research.

When visually compared with the terrain map (Figure 5.2a), the livestock grazing suitability index map (Figure 5.8, left) shows higher index values in the central valley and plains, while the escarpments and upper slopes to mountain tops show the least. Similar patterns of grazing intensity appear in the participatory maps (Figure 5.1). This implies that, of the criteria evaluated, terrain may have the dominant influence on grazing distribution. This may be attributed to the influence of elevation and slope on livestock accessibility as well as on soil and micro-climate that affects vegetation. Local participants indicated that most of the species of livestock grazing preference are located in the lower elevations and from the EBF analysis, the map with the least uncertainty used the distribution of vegetation species as criteria. Comparable studies (e.g., Kohler *et al.*, 2006) found that some spatial patterns of cattle effects such as dung distribution were positively correlated with slope, rockiness and vegetation openness.

Likewise, Turner and Hiernaux (2002) found that the distribution of livestock grazing reflected local patterns of land use, topography, vegetation, settlements, and water points. During the SMCE, the highest weight was assigned to the vegetation. As seen from section 5.1, there are other factors that may influence the index. These include: management structures (e.g., fencing, placement of salt; watering facilities); interaction effects related to the spatial distribution of preferred and non-preferred plant communities/forage species; forage conditions; and animal behavioural patterns (Bakker, 1989; Kohler *et al.*, 2006; Stuth, 1991).

The grazing intensity patterns shown in the maps drawn by the local experts and those indicated by the suitability index indicate considerable level of the participants' understanding and capacity to integrate various environmental factors. Tables 5.1 and 5.2, show that some of the criteria (e.g., livestock numbers, vegetation species, and altitude) were considered by experts and in the SMCE. The two separate evaluations, however, miss the benefits of concerted knowledge, and the list is not exhaustive. From a related PGIS process (Bemigisha *et al.*, in preparation), pastoralists provided a greater number of mapping criteria (37%) and other spatial data on grazing intensity than the experts although the experts represented data better on the maps. Although the purposes of this analysis led to the exclusion of the maps drawn by the pastoralists, the mapping process may benefit from their knowledge (e.g., Turner and Hiernaux, 2002). The experts represented better the grazing intensity, possibly because, in addition to their interaction and experience with the grazing activities and land resources of the park, they had more experience with maps and with synthesizing criteria. We therefore expect a modified or more accurate index if criteria scoping and integration within PGIS is combined with the SMCE process, and if local pastoralists are fully involved in the process.

The spatial data integration and analysis tools such as EBFs and SMCE were useful in verifying the usability of PGIS products through integration, testing and ensuring consistency of local knowledge in classification. It is, however, questionable as to how adjusting the parameters and tools in the two methods would affect the comparison results. Further investigation is needed to see if these tools may together be directly embedded within the PGIS processes, but caution is needed on possible encouragement for experts to implement a system beyond the local pastoralists' understanding, thus reducing the latter's locus of control (Jankowski, 2004).

5.5 Conclusions

The use of PGIS was useful in eliciting local spatial knowledge and generating relevant criteria for classifying grazing intensity. PGIS made it possible for local participants who had not drawn maps before understand the decision-making process in map classification using different criteria. It was also possible for the participants to interactively visualize oral interview data and map attribute spatial data in a GIS.

The variations in uncertainty in PGIS-based classification can be represented adequately by increasing differences in values for *Uncertainty* between classes, while maintaining the arithmetic relationship between *Belief*, *Uncertainty* and *Disbelief*. By evaluating two sets of EBFs, it was possible to make a choice as to the more realistic EBF estimations. This highlights the usefulness of developing and evaluating alternative sets of EBFs.

Class-area-weighted averages of EBFs show that the maps with the lowest uncertainty were based on the distribution of palatable vegetation species, suggesting that this criterion may be the better criteria for mapping grazing intensity than for example, terrain and animal numbers, but it does not adequately represent a measure of grazing intensity. The definition of grazing intensity that included vegetation species composition and abundance and a livestock utilization factor may be considered. The successful application of EBFs for representing classification uncertainty depends on propositions about grazing intensity. The proposition evaluated in this study was based on the given PGIS-based maps that were drawn using the limited criteria that defined a grazing intensity class. Depending on the suggested definition of grazing intensity, then an alternative proposition based on forage condition (ground cover quality and quantity) and a livestock utilization factor is recommended for future work.

The number of criteria used by the local experts to draw the grazing intensity maps apparently influences classification uncertainty. The local experts seemed more certain when using one criterion than when using more than one. Applying spatial multiple criteria tools may be a viable approach to synthesizing the different criteria, but these need to be tested for local participatory application.

The final integrated map of uncertainty indicates areas where local experts, with one or more pieces of geo-information, are confident of providing a classification. By showing the level of classification

uncertainty, the study highlights the level of confidence with which the PGIS maps can be used in further analysis and modelling.

Based on this study, a method for integrating and representing classification uncertainty and establishing the reliability of PGIS maps can be developed for livestock grazing distribution and other disciplines. To achieve this, however, further investigation is needed to establish a standardized measure for the classification of livestock grazing intensity.

The study has shown consistency between grazing intensity classification by local experts, and landscape factors that influence grazing distribution in the study area. It was found that the higher the grazing suitability index, the higher the grazing intensity. However, a Pearson correlation coefficient of 0.35 ($P < 0.01$) showed a weak relationship. Although weak, the established relation is important for understanding how spatial variables may be better evaluated in local participatory mapping, specifically to improve classification and planning of livestock grazing and other landuse systems.

EBFs and SMCE improve the reliability and consistency of the classification and spatial planning process, because they aim at reducing the subjectivity in the analysis. The same task can be performed by different people and still give the same or a similar result. In this study, the spatial data integration and analysis tools (EBFs and SMCE) are proven to test and ensure consistency and reliability of local knowledge in PGIS-based classification. This shows that the improved methods for eliciting this knowledge and ascertaining its reliability are also complementary.

A method that adequately integrates the knowledge of the pastoralists is needed, specifically, focused on building their experience with maps and synthesizing criteria. These skills may have enabled the experts to spatially represent the grazing intensity on a map. Therefore, a modified or more accurate grazing suitability index may be obtained if the scoping of the criteria by the local experts is improved through integrating SMCE with PGIS and by integrating knowledge from local pastoralists. Further improvement may be realised if mapping grazing intensity measures are based on integrating various vegetation parameters such as species composition, ground cover, quantity and quality, which may be estimated using hyperspectral remote sensing. Future research should therefore investigate how local pastoralists and experts can be guided to investigate and apply EBFs based on prepositions that consider the

various parameters. This promises a higher potential for local knowledge to be used in empirical studies including hyperspectral remote sensing research that are often limited by baseline information. In the next chapter, a synthesis that conceptualizes the linkages between hyperspectral remote sensing and geo-spatial tools related to local participation is presented.

Chapter 6

Synthesis

Spectral and human sensors in a three-faceted mapping model of livestock grazing intensity and vegetation

6.1 Introduction

Grazing intensity affects the physiognomy and species composition of vegetation (Bakker, 1989; Center, 2005). Hence, reduction or intensification of grazing may lead to changes in species composition and vegetation structure. The response of vegetation to grazing intensity has been intensively investigated (e.g., Bakker, 1989; Dayan, *et al.*, 1981; Johnson *et al.*, 1983; Kuijper, *et al.*, 2004; Olf *et al.*, 1999). A wide range of variables have been investigated across levels of biological organization. These range from cells to ecosystems including processes at the level of the plant from plant physiology to competition involving plant-plant interactions (e.g., Berendse *et al.*, 1992; Gates 1980; Damgaard, 1999; Fetene, 2003), plant-herbivore interactions (e.g., Olf *et al.*, 1999; Arsenault and Owen-Smith, 2002; Humphrey and Schupp, 2004). Other variables concern the more pragmatic question of which grazing intensity to maintain in order to achieve sustainability in rangeland management, an issue frequently associated with carrying capacity (e.g., Bakker, 1989; Morris *et al.*, 1999; Pickup and Chewings, 1988; Rasmussen *et al.*, 1999; Turner and Hiernaux, 2002). Just as the above investigations have spanned various variables and processes, the studies also differ in their consideration of spatial representation (i.e., spatial or non spatial).

The rich literature on grazing impacts can, therefore, further be stratified into those considering and representing the spatial context in which grazing influences vegetation and those that do not. A few studies show that grazing intensity and vegetation response are spatial phenomenon, and spatial tools have been applied (e.g., Edwards *et al.*, 1999; Kirkpatrick *et al.*, 2005; Landsberg *et al.*, 2003; Mwendera *et al.*, 1997; Numata *et al.*, 2007; Pickup and Chewings, 1988; Rasmussen *et al.*, 1999; Turner and Hiernaux, 2002).

The spatial scales used also vary and the studies have rarely demonstrated the linkage between knowledge of the effect of grazing and competition on individual forage plant species on the one hand, and spatial knowledge of grazing intensity at the broader landscape level on the other.

The various methods of investigation and accruing knowledge provide insight into grazing intensity and its effect on vegetation, but this may be improved through a unified geo-spatial information framework. The frameworks developed in other sciences, for example in standardized vegetation classification (e.g., Kent and Coker, 1992; Orloci, 1975; UNESCO, 1973) motivated this research to investigate methods for mapping livestock grazing intensity and interactions with vegetation.

Existing studies form a basis for a geo-spatial information framework for studying grazing intensity and vegetation. The use of remote sensing to capture vegetation variables such as above-ground biomass and canopy height, helps to provide the information over large areas in a more timely and objective manner, therefore reducing the time and labour costs that may be needed for field surveys (Tueller, 1989). Improvements in this technology show that the estimation of the vegetation variables has improved through the use of hyperspectral remote sensing (e.g., Skidmore *et al.*, 2005; Chopping, 2003). This technique involves the use of high spectral resolution sensors with at least 100 channels of data, and less than 10 nm band widths. This enables the capture of the spectral details that may not be captured by broad band-based remote sensing (Curran, 1994).

To the existing framework, this research has added investigation of how defoliation and species cultures affect plant biophysical variables (dry matter yield and height) and subsequently, regrowth and competitive ability of the forage species; and if hyperspectral remote sensing may be used to estimate these effects.

This research also investigated the use of local knowledge, specifically, spatial knowledge from the pastoralists and local range ecology experts using participatory GIS (PGIS). PGIS has been used for similar purposes in other studies (e.g., Rasmussen *et al.*, 1999; Turner and Hiernaux, 2002), but what has been explored less is investigation of local people's capacity in handling multiple spatial objects in classification and evaluation and classification uncertainty in PGIS map products. This research, therefore, included the estimation and representation of classification uncertainty using GIS-based evidential belief functions (EBFs) and Dempster's rule of

combination (Dempster, 1967; Shafer, 1976). In addition, the application of spatial multicriteria evaluation (SMCE) tool in testing local knowledge for mapping livestock grazing intensity and grazing suitability evaluation was also investigated.

The specific study area was Majella National Park, Italy. Transhumant livestock grazing (mostly sheep, goats and cattle) has been maintained but forage resources are declining (Bignal, 1998; Bignal and Pienowski, 1999). It has been noted in section 1.1 that the key information requirement for managing livestock production together with conservation is the response of plant species to grazing (Gutman *et al.*, 2001). Existing approaches used have not sufficiently addressed the problem of estimating grazing intensity and vegetation response (Hardy *et al.*, 1999).

This chapter comprises a synthesis of the different methods for mapping and understanding the effects of grazing intensity on vegetation investigated in this research and a list of main conclusions. The research framework is based on three facets: three geo-spatial information technologies, three kinds of knowledge and three levels of investigation. Three geo-spatial technologies (GIS, RS and PGIS) take a central position in this model (Figure 6.1).

6.2 Bridging hyperspectral remote sensing, GIS and PGIS: the concept

The concept of the three-faceted model is illustrated in Figure 6.1. Based on the methods investigated in this study, each of the geo-spatial tools, that is, hyperspectral remote sensing, GIS and PGIS may be viewed as functionally distinct. Hyperspectral remote sensing helps to provide detailed information on the effects of defoliation and competitive interactions on plant biophysical variables (e.g., dry matter yield and height). This makes it possible to monitor the regrowth and competitive ability of the species (Chapter 2, 3, and 4). Based on this understanding, species composition and vegetation patterns may be predicted. Using spatial oriented EBFs and SMCE in the PGIS-based analysis reflects the role of GIS in supporting local participation and in the evaluation of classification uncertainty of the PGIS products. GIS and PGIS complement the collection and integration of the local people's knowledge at broader landscape scale, which may generate valuable baseline information for empirical studies including hyperspectral remote sensing research (Chapter 5).

Therefore, although functionally distinct, the different kinds of geo-spatial tools complement each other and support research through

the different kinds of knowledge they help to provide (Figure 6.1). For example, GIS techniques are associated with PGIS through spatial representation of knowledge. Using GIS, local rangeland ecological knowledge, scientific research knowledge and knowledge from local pastoralists can be spatially represented. At the same time, local knowledge complements scientific research knowledge (e.g., Prins and Wind, 1991; Turner and Hiernaux 2002; Van der Hoeven *et al.*, 2004; Minang and McCall, 2006) and this may be at the laboratory experiment level where remote sensing results may be applied or field level where remote sensing and GIS may be used (e.g., Armitage *et al.*, 2000; Mathur *et. al.*, 2002, Schmidt and Skidmore, 2001).

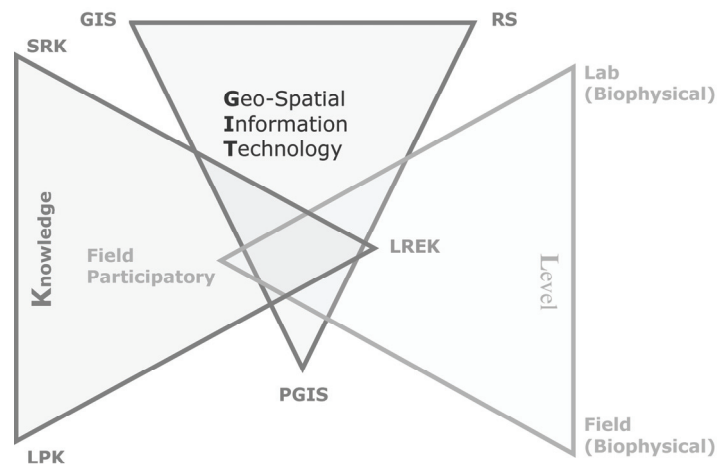


Figure 6.1 The three-faceted analysis framework for mapping grazing intensity and its effect on vegetation using GIS, RS and PGIS (Geo-spatial information technology tools using different kinds of knowledge at laboratory, and field level. GIS = geographic information system; RS = remote sensing, LREK = local rangeland ecological knowledge, SRK = scientific research knowledge, LPK = local pastoralists' knowledge.

The three-faceted model may help to provide different kinds of knowledge needed to manage livestock grazing and vegetation in transhumant Mediterranean areas. Based on the results of this research (see summary in sections 6.3.1 and 6.3.2 below), it is seen that high spectral resolution sensors detect details of the effect of grazing and competitive interactions on forage plants through narrow band channels across the electromagnetic spectrum, while the local people provide information on a few broad grazing intensity classes (Figure 6.2).

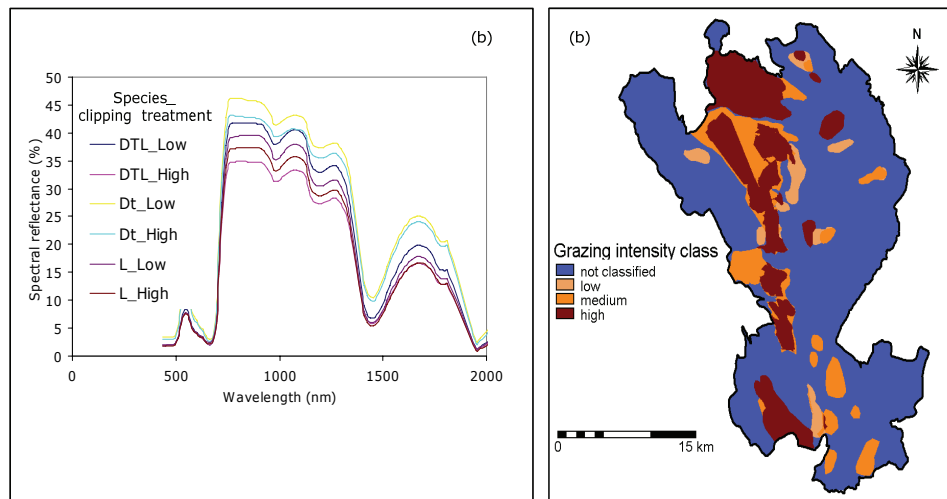


Figure 6.2 Mean hyperspectral reflectance of different combinations of species and clipping treatments obtained by use of a spectroradiometer in a laboratory experiment at 18 weeks after sowing (a) and the grazing intensity map comprising different levels of grazing intensity, obtained from the PGIS process. Note the detailed information in the hyperspectral data versus the broad classes of grazing intensity in the PGIS-based map. Legend codes for (a): Dt = *Dactylis glomerata*; L = *Lolium multiflorum*, and DtL = mixture of Dt and L).

Therefore, the contrast in knowledge and scale is that the spectral sensor provides detailed information on the condition and patterns of vegetation while the local pastoralists and experts provide information on more coarse scale grazing intensity patterns.

6.3 Utility of the three-faceted model: this case study

In the current research, we demonstrate the use of different kinds of geo-spatial information tools and different kinds of knowledge that can be provided at different levels of analysis. The study site was Majella National Park, Italy, where the park management and pastoralists face a challenge of pasture land abandonment, changes in vegetation from grasslands to bush and forest, and declining pasture resources.

The field study area formed the basis for a greenhouse experiment to understand the interactive effects of forage species types, cultures (mixed or monoculture) and defoliation intensity on two growth traits, dry matter yield and height. This enabled the determination of regrowth capacity and competitive ability of the studied species. Based on the same experiment, we tested if changes in narrow-band spectral reflectance, indices and the red-edge can be used to

determine the regrowth and competitive ability of forage species. The use of local knowledge from pastoralists and experts through the application of participatory GIS (PGIS) at field landscape level was investigated. The emphasis was on establishing if local participants could identify and use spatial variables or criteria for mapping grazing intensity.

6.3.1 Hyperspectral remote sensing of defoliation intensity and competitive ability of forage grass

Studies suggest that the competitive performance of individual plant species determines vegetation species composition and patterns (e.g., Armitage *et al.*, 2000; Dayan *et al.*, 1981; Dovrat *et al.*, 1980; Landsberg *et al.*, 2003; Noy-Meir and Briske, 2002). The competitive ability of the individual plants influences inter-specific competition and therefore, affects composition and structure of plant communities (Tilman, 1988). In order to understand the effect of grazing on vegetation, knowledge about the competitive ability of the vegetation species is required.

Narrow band vegetation spectral features (less than 10 nm) have provided opportunities to estimate vegetation parameters such as biomass and leaf biochemical components (Mutanga and Skidmore, 2004; Thenkabail *et al.*, 2000). Defoliation by grazing and browsing affects plant growth variables such as biomass (Grime, 1979). Consequently, the estimation of the effect of livestock grazing on vegetation has been improved by using models that depend on spectral response (e.g., Numata *et al.*, 2007; Hill *et al.*, 2004). A new question addressed in this research was whether different types of species and species cultures (monoculture or mixed), if combined with defoliation by clipping, significantly affect narrow band spectral reflectance, indices and the red-edge position. We show that short term (5-weeks interval) changes in dry matter yield and height can be studied using hyperspectral remote sensing (chapters 2, 3 and 4). Because dry matter and height indicate competitive ability of plant species (Grime, 1979), hyperspectral remote sensing may be used to study regrowth and competitive ability of forage species.

First, we showed that using a greenhouse clipping experiment, the competitive ability of co-occurring forage grass species under different species cultures and clipping intensities can be understood (Figure 6.3). These effects were assumed to occur in a nested design in which the clipping events occur within different levels of clipping intensity and the intensity levels pertain to different species cultures (monoculture or mixed) of different types of species. A nested

Analysis of Variance model was used in which clipping time was nested within the clipping intensity, species culture and species interaction, as illustrated in Figure 6.3, and expressed as follows:

$$G = (\text{Species} * \text{Culture} * \text{Clipping}) / \text{Time}$$

where G = growth response variable (height or dry matter yield), time = clipping time after sowing (T2: after 13 weeks, and T3: after 18 weeks), culture = mixed and monocultures, and clipping = clipping intensity (low: 15 cm and high: 10 cm above the ground).

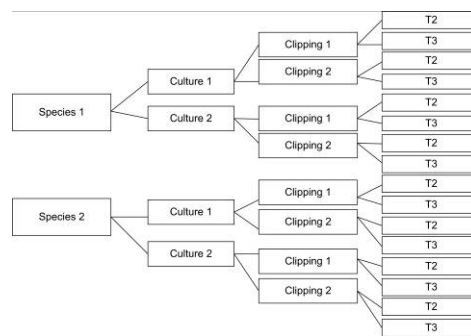


Figure 6.3 A nested design of the greenhouse experiment data to estimate the effect of clipping time, clipping intensity, cultures and species type on regrowth in height and dry matter yield of two livestock forage species. Time (T2: 13 weeks after sowing and T3:18 weeks after sowing) was nested within clipping intensity (clipping 1 and clipping 2) which was nested within species cultures (mixed and monocultures) and species types (species 1 = *D. glomerata*; species 2 = *L. multiflorum*).

Because herbivores graze selectively, the effect of varying grazing intensity on the spatial distribution and abundance of the vegetation species, especially of those species preferred for grazing need to be understood. Some studies show that grazing may reduce the population density of the species (e.g., Noy-Meir and Briske, 1996), but other studies show that plant species increase their productivity when subjected to defoliation damage (e.g., Boyd and Svejcar, 2004; Cooper, 1964; Loud *et al.*, 1990; Riba, 1998; Wolfson, 1999). In the current research, the regrowth rate of *Lolium multiflorum* (usually preferred by livestock grazers) was compared with that of the less preferred species, *Dactylis glomerata*. *D. glomerata* was negatively affected by the presence of its neighbour *L. multiflorum* (Figure 6.4). When the two species were mixed, the comparison of their regrowth showed that the mean regrowth of *L. multiflorum* was significantly higher than that of *D. glomerata* ($P < 0.0001$). The results suggested higher competitive ability of the former species. This was contrary to

our expectation that selective clipping would lead to higher competitive ability in *D. glomerata*

Some studies have shown that the height advantage at an early growth stage in plant species leads to higher competitive capture of incident light and photosynthetic efficiency in the taller species than the shorter species (de Wit, 1965; Pronk *et al.*, 2007; Grime, 1979). Our investigation to understand the effect of grazing and species mix on two growth characteristics, that is, increase in height and dry matter (DM), revealed that clipping had greater effect on height regrowth than on dry matter for both species, but the species that attained higher dry matter yield showed higher competitive ability. The clipping and species mix was found to affect more the regrowth of *D. glomerata* which usually grows taller than *L. multiflorum*, a species that grows relatively larger in lateral stature (Hannaway *et al.*, 1999; Hubbard, 1968; Duke, 1983). The earlier germination and larger lateral size of *L. multiflorum* may have led to the suppression of the inherent characteristic of *D. glomerata* to grow taller.

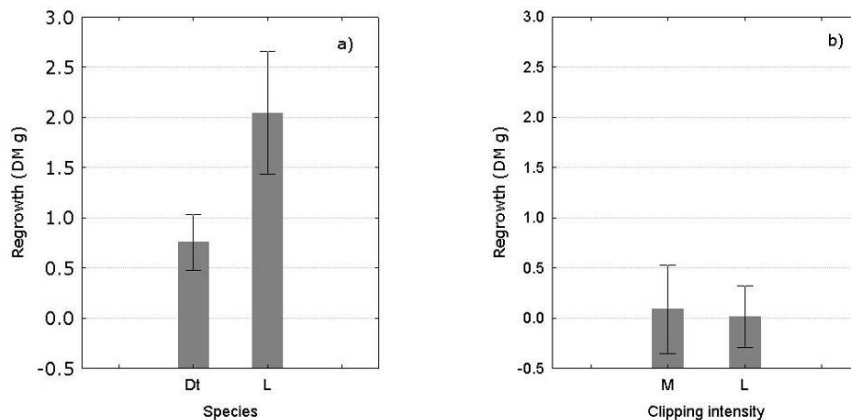


Figure 6.4 Mean regrowth of (a) *D. glomerata* (Dt) and *L. multiflorum* (L) under selective clipping, and (b) *D. glomerata* under medium clipping in mixed cultures of selective treatment (M-Selective) and uniform treatment (M-Uniform). The vertical lines (whiskers) on top of the bars indicate 95% confidence intervals.

Investigating competitive dynamics using this kind of experiment at field level may be costly and challenging because of the various species involved especially if the investigation covers a large geographical area. The new innovative techniques of hyperspectral remote sensing help to obtain detailed spectral, spatial and temporal information, thus helping to provide the required information detail, content and frequency of observation. The possibility may stem from

the association of vegetation variables that indicate competitive ability such as dry matter yield.

To test if hyperspectral remote sensing may be used to estimate the above effects, a spectroradiometer (350 nm to 2500 nm) developed by Analytical Spectral Devices (ASD) Inc., Boulder, Colorado, USA) was used to obtain spectral reflectance. Spectral indices and the red edge position for the different species and clipping treatments were obtained. We showed that the different intensity levels of grazing (emulated by clipping) when combined with different kinds of species mixes affect specific spectral features. For example, the band at 694 nm was highly significantly affected ($P < 0.001$), (Chapter 4).

Spectral discrimination is known to be influenced by phenological developments of different species (Campbell, 2002). The phenological developments in the species may have had an influence in this study. A shifting of the region of best discrimination from the visible to the NIR was observed and it coincided with an increase in the dry matter yield of the species whilst the level of discrimination of the different pairs of spectra for the various treatments declined. This suggests that the initial measurement time (T2: after 13 weeks) may be a better time to detect the effect of the treatments on reflectance of the studied species than T3. Further investigation is needed on how different temporal scales of observation relate to the effects of clipping and culture treatments on different forage species.

A number of spectral features showed potential for estimating the effect of different species culture and defoliation treatments on the growth and competitive ability of the forage species. These included the physiological reflectance index (PRI), the Carter index, R_{694} , the ratio of the Transformed Chlorophyll Absorption in Reflectance Index to the Optimized Soil-Adjusted Vegetation Index (TCARI/OSAVI) and the red-edge position. The PRI showed the highest sensitivity (about 100% average increase), (Figure 6.5) and also showed a linear positive response to both height and dry matter at T3, which was not the case at T2 (Figure 6.6). Other studies (e.g., Peñuelas *et al.*, 1994; Sims and Gamon, 2002), have associated the PRI with the carotenoid/chlorophyll ratio. The association was attributed to leaf development and possibly plant growth. This means that the changes in the PRI found in this study, may be attributed to changes in the ratio of carotenoids to chlorophyll between the two clipping events. Other studies show similar changes in spectra that involve plant growth (e.g., Baghzouz *et al.* 2006; Gupta *et al.*, 2001), suggesting that spectral indices may be related to different stages of plant growth. Therefore, the PRI may be used to study competitive ability

of forage plants because of its sensitivity to the growth changes in the plant characteristics that indicate competitive ability.

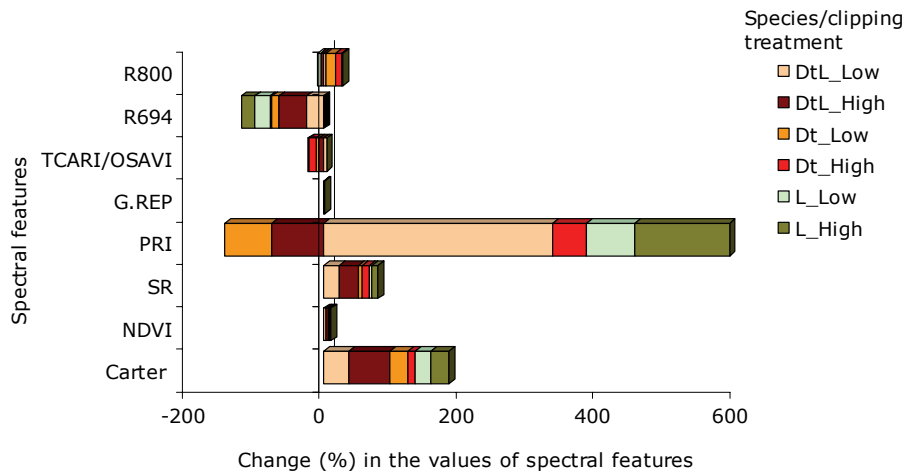


Figure 6.5 Change (%) in the values of spectral features between T2: 13 weeks and T3: 18 weeks after sowing for the different combinations of species and clipping treatments. Codes: NDVI = normalized difference vegetation index, SR = simple ratio, PRI = physiological reflectance index. G.REP = red-edge position using the Guyot and Baret (1988) equation. TCARI/OSAVI is the ratio of the Transformed Chlorophyll Absorption in Reflectance Index (TCARI) to the Optimized Soil-Adjusted Vegetation Index (OSAVI). "R" in R_{694} and R_{800} denotes reflectance at the specified wavelength. Legend codes: Dt = *Dactylis glomerata*; L = *Lolium multiflorum*, and DtL = mixture of Dt and L).

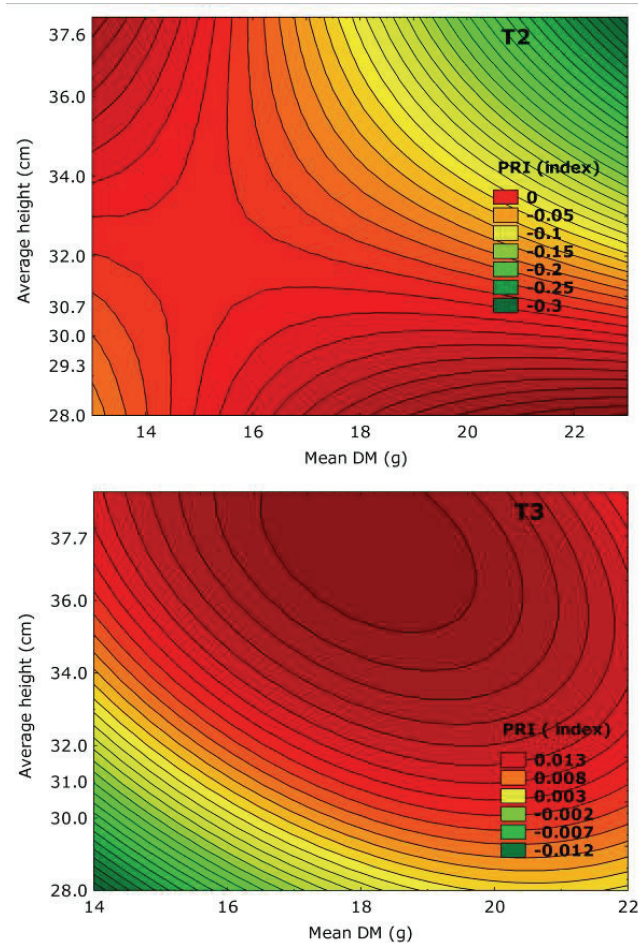


Figure 6.6 3D contour plots showing change in the response of the physiological reflectance index (PRI) to the interaction effect of height and dry matter in the species at T2: after 13 weeks (top) and at T3: after 18 weeks (bottom).

The results are encouraging for further research on remote sensing of defoliation intensity and competitive ability of different co-occurring forage species. *L. multiflorum* consistently showed a higher regrowth rate in the mixed species as described earlier in this section and also in chapters 2 and 3. This means that the higher regrowth rate of *L. multiflorum* in the mixtures may be the reason why reflectance in the mixed species is more significantly different from the other species, *D. glomerata*. Furthermore, the PRI showed a linear positive response to both height and dry matter at T3, which was not the case at T2, suggesting sensitivity to both dry matter yield and canopy structure.

This shows that the PRI may be used to directly estimate the growth variables such as dry matter yield and canopy height. The relationship between spectral reflectance features and these growth variables should, therefore, be tested at field level to see if we may directly use reflectance data as a simpler and quicker alternative to the existing canopy height and pasture growth models.

6.3.2 Using local knowledge at landscape level

Local knowledge contributes valuable information to research and management of resources especially when data from empirical studies are limited or not available (e.g., Store and Kangas, 2001; Van der Hoeven *et al.*, 2004). In this study we demonstrate the use of local knowledge in the mapping of grazing distribution just as other studies have used local knowledge in scientific investigations of natural resources management. Participatory geographic information systems (PGIS) were found to complement conventional mapping by adding the perspective of local knowledge (e.g., Close and Hall, 2006; Scholz *et al.*, 2004). Studies (e.g., Turner and Hiernaux, 2002) have demonstrated the use of GIS in livestock studies that involve local pastoralists. The use of PGIS in this study aimed to enlist local spatial knowledge including knowledge from local pastoralists in the classification of grazing intensity in Majella National Park, Italy. In addition to these methods, was the evaluation of map classification uncertainty (Figure 6.6), and the comparison of the PGIS maps with an independently developed grazing suitability index (Figure 6.8).

Although valuable in terms of knowledge content, the reliability of local participatory maps may be questionable. Local rangeland ecology experts and pastoralists operating in the park classified the park into low, medium and high livestock grazing intensity. The maps drawn by local pastoralists did not meet a requirement for evaluating classification uncertainty because of the discrepancies in the number of classes used. The maps drawn by the local experts were also not synthesized into a final grazing intensity map. The later weakness provided an opportunity to investigate the use of evidential belief functions (EBFs) and Dempster's rule of combination (Dempster, 1967; Shafer, 1976) to represent classification uncertainty and integrate the PGIS-based grazing intensity maps. This is a new approach for testing the reliability of spatial local knowledge or PGIS map products (Chapter 5).

The application of EBFs for representing classification uncertainty depends on the formulation of a proposition on grazing intensity. In the current research, the proposition was that: "*This area or pixel*

belongs to the high, medium, or low grazing intensity class because the local expert(s) says (say) so," but this does not adequately represent measures of an intensity class. This may be because of the subjective nature and application of mapping criteria used to draw the maps. An alternative proposition based on vegetation composition, ground cover, quality and quantity (Skidmore *et al.*, 2005) may be a better alternative if a livestock utilization factor is integrated as suggested by Bakker (1989). Future studies should investigate how local pastoralists and experts may be involved in applying hyperspectral remote sensing, EBFs and SMCE based on such a proposition.

We also found that the application of EBFs depends on the number and nature of criteria used by the local participants. For example the local experts appeared to be more confident when using one criterion than when using more than one classification criteria Table 6.2 and Figure 6.7. This suggests that classification uncertainty may be minimized by applying spatial multiple criteria tools to synthesize the different criteria (Chapter 5).

The comparison of the grazing intensity map with the grazing suitability index map showed that the higher the grazing intensity class, the higher the grazing suitability index, suggesting that the two maps were related. This suggested further that the local experts had considerable level of understanding of the identification and application of mapping criteria but the understanding may not be adequate for grazing intensity classification. The inadequacy was shown by a weak correlation between the grazing intensity map and a grazing suitability index ($r = 0.35$ ($P < 0.01$)). This shows that criteria identification and evaluation may have been difficult for the local experts.

Table 6.2 Criteria used by local experts for classifying grazing intensity, and the interpretation of the criteria given by the participants. Map1, Map2, Map3, Map4, and Map5 are the grazing intensity maps drawn by either group or individual participants.

Criteria	Interpretation	Maps
Animal numbers	The higher the numbers, the higher the intensity	Map5, Map3
Altitude	The higher the altitude, the lower the intensity	Map5, Map1
Droppings	The more the droppings, the higher the grazing intensity	Map5
Vegetation species	The higher the composition of palatable species, the higher the intensity	Map4, Map2
Watering points	The nearer the area to watering points, the higher the intensity	Map2

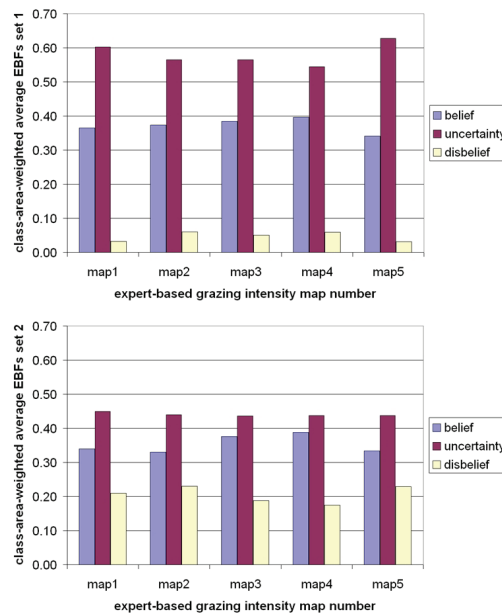


Figure 6.7 Alternative estimated/derived EBFs: different class-area-weighted average for *Uncertainty* per map in set 1 (top) and the estimated/derived EBFs in set 2 that seem to have almost equal class-area-weighted average for *Uncertainty* per map.

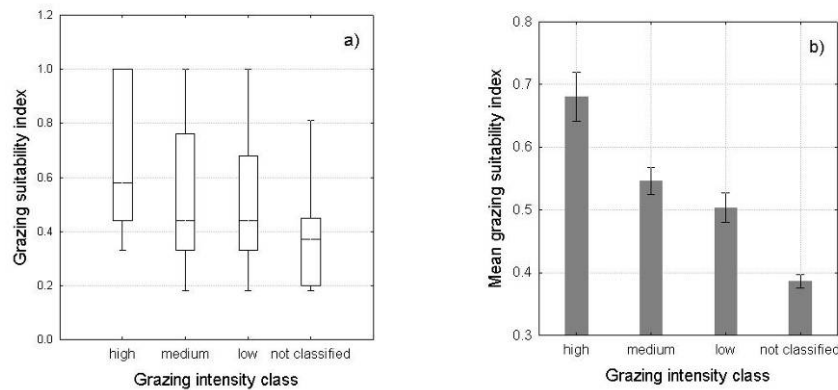


Figure 6.8 (a) Box plot showing the variability in the dataset, and (b) mean values of grazing suitability index within each grazing intensity class. Vertical bars in (b) denote 0.95 confidence intervals.

A question for future research pertains to the subjectivity in deriving EBF values as can be seen in the differences between two sets of EBFs in figure 6.7. This means that another step in evaluating alternative EBF sets may be required. Therefore, the results from EBF assessments need to be cross-validated before they can be considered for use in evaluating classification uncertainty.

In summary, the study shows that local people have valuable information on grazing intensity. PGIS was useful in eliciting local spatial knowledge and generating relevant criteria for classifying grazing intensity. The results of this study may be used to establish a method for integrating and representing classification uncertainty and establishing the reliability of PGIS maps of grazing intensity. In order to achieve this, a standardized definition and measure for the classification of livestock grazing intensity needs to be established.

6.4 Implications of the study to conservation and transhumant livestock landuse planning and policy

Integrating transhumance with conservation has been promoted because of various advantages. From section 1.1 we have seen that livestock grazing may positively affect vegetation for livestock production purposes by increasing productivity of palatable species (Van Wieren, 1996; Voeten, 1999; Prins and Nell, 1990). The income generated from meat and dairy products also stimulates the maintenance of livestock grazing in wildlife conservation areas (Prins *et al.*, 2000; Stevens, 1997; Voeten, 1999). This may have positive

side effects on the conservation values as grazing may create gaps which promote less productive plant species and a higher diversity of the vegetation (Bakker 1989), and associated faunal communities.

Rural development plans have been prepared to protect pastures and to enhance livestock production in the transhumant Mediterranean areas in order to maintain the biodiversity typically associated with these pastoral systems (Bignal, 1998; Bignal and Pienowski, 1999), but landuse allocation problems have not been adequately resolved in some areas. In Majella National Park, the pastoralists hire grazing land administered by the park but the allocation is not enforced and boundaries have not been demarcated. This means that the shepherds can access areas that have been zoned for other uses (Section 5.2.5.2; Figure 5.2b). A comparison of mean values of grazing suitability index within each grazing intensity class (Figure 6.8) reveals that livestock grazing may be distributed where it is not most suitable. Moreover, the study does not take into account grazing attributed to the wild herbivores in the study area.

Examples from the African savanna ecosystems show that the spatial distribution of livestock within conservation areas may result in competition between wildlife and livestock (Prins *et al.*, 2000). This leads to land allocation problems if decision choices depend on economic costs of livestock keeping to wildlife management. These decisions can be influenced by resulting disease transfer, negative effect of livestock numbers on wildlife animal numbers, and associated human activities and landuse (Prins *et al.*, 2000). Further consideration for making land allocation decisions is the wildlife potential to produce more viable economic products through tourism and recreation (Prins *et al.*, 2000). For such or similar reasons, the transhumant livestock activities in the Mediterranean areas may continue to decline. Consequently, availability of forage for livestock may decline further due to the associated changes in vegetation from grasslands to bush and forest (Pienowski and Bignal, 1999).

Research should therefore be focused on establishing a landuse allocation system that enables sustainable co-existence of wildlife conservation and pastoralism. This requires the understanding of grazing intensity and vegetation distribution. The use of remote sensing to capture vegetation variables such as above-ground biomass, and canopy height helps to provide timely and objective information over extensive areas. This helps to reduce the time and labour costs that may be needed for field surveys. The results of this research (Chapters 2, 3 and 4) show that short term experiments can be used to study the effects of defoliation intensity and competitive ability of forage grass using remote sensing. The study promises

more efficient monitoring of the growth and competitive ability of the species using hyperspectral remote sensing. This also suggests that the monitoring of the preferred species that are at high risk of decline can be improved. If the performance of individual species is understood, then vegetation species composition and patterns may be better predicted using hyperspectral remote sensing.

Using PGIS at field landscape level, we found that local pastoralists and experts have valuable spatial information on grazing intensity and they could identify and apply spatial criteria to delineate grazing intensity classes. This is be useful baseline information for the management of grazing activities and vegetation as well as for further research including that on hyperspectral remote sensing. Therefore, combining hyperspectral remote sensing GIS and PGIS may lead to better understanding of the distribution of grazing intensity and the condition and spatial patterns of forage vegetation than has been done using conventional methods discussed in section 1.3.1.

The different geo-information technologies and the contrasts in knowledge and scale benefit research and rangeland management. Hypespectral remote sensing provides detailed information about various vegetation parameters affected by defoliation and competitive interactions in vegetation species through contiguous narrow band channels, whereas the local people perceive broad classes of grazing intensity based on a few criteria.

6.5 Main conclusions

In this research we demonstrate the combined use of hyperspectral remote sensing, GIS and local participation for investigating the mapping and understanding of livestock grazing intensity and its interactions with vegetation in transhumant Mediterranean areas. Different but complementary kinds of knowledge have been obtained at different levels of investigation: greenhouse laboratory experiment level and at field landscape level.

A statistical nested analysis of greenhouse experiment data contributed to the understanding of the interactive effects of grazing and species mix on growth characteristics (weight and height) of forage grass, *D. glomerata* and *L. multiflorum*. Results showed that *L. multiflorum* attained higher dry matter, consistent with higher regrowth and regrowth rate, thus, it was considered the better competitor. The statistical results confirmed that, under uniform grazing rather than grazing intensity, the higher regrowth of *L. multiflorum* compared with that of *D. glomerata* was largely

attributed to the type of species and culture. Selective clipping did not lead to higher competitive ability of *D. glomerata* as expected.

The approach used in this experiment to study regrowth and competitive ability of co-occurring livestock forage species in relation to different clipping intensities and species types and cultures may be applied at field level. For extensive heterogeneous rangeland areas, the efficient remote sensing techniques that provide detailed information on various vegetation variables at high frequency of observation are needed.

Using hyperspectral remote sensing, we have shown that changes in narrow-band spectral reflectance, indices and red-edge can be used to estimate the regrowth capacity and determine competitive ability of forage species. It was shown that clipping and species cultures (monoculture or mixed) significantly affect spectra and this effect progresses from the visible to the NIR region over time. For example the species cultures had a significant effect ($P < 0.05$) in the visible (red) region by the initial measurement time, while the clipping effect was highly significant ($P < 0.001$) only in the NIR. At a later measurement time, the effect of clipping was shown in more bands both in the visible and NIR. The shifting of the region of discrimination from the visible to the NIR seemed to coincide with an increase in dry weight and height and decreasing level of discrimination of spectra for the different pairs of treatments. The results suggest that the initial measurement time (T2: after 13 weeks) may be the better time to detect the effect of the treatments on reflectance of the studied species than T3, but how this relates to the effects of clipping and culture treatments on forage species needs further investigation.

The spectral response in mixed cultures was more comparable to that of the *L. multiflorum* monoculture than to that of the *D. glomerata* monoculture. This suggests that the shifting of the effects to the shortwave region and the changes in the PRI values that occurred mostly in the mixed cultures were possibly related to the higher competitive ability of *L. multiflorum*. The response of the index to height and dry matter in the species reflected this possibility because, these traits are indicators of regrowth capacity and competitive ability. A negative linear relationship between PRI and the forage growth variables (height and dry matter) was shown at T2, but a positive relationship was shown at T3, suggesting that the PRI increased with increased photosynthetic material but the specific stages of growth of species that may be studied using the PRI need to be further

investigated. Other indicators such as stress tolerance need to be investigated.

The approach used may be a simpler alternative to the existing canopy structure and pasture growth models and may be extended by further investigation of a wider variety of spectral features in assessing the competitive ability of co-occurring forage species.

At the field landscape level, we showed that local people have valuable information on grazing intensity. The process of identifying and using criteria for mapping grazing intensity revealed that the pastoralists and experts have reasonable understanding of the grazing system. Using their understanding of the system, the local participants were able to classify the park into classes of low, medium and high livestock grazing intensity. The local experts spatially represented their knowledge more accurately than the pastoralists possibly because the latter combine local experience of the area with mapping familiarity through their scientific training and work experience.

PGIS is shown to be a useful mapping tool, but because mapping errors aggregate when different sources of data are combined, evidential belief functions (EBFs) and spatial multiple criteria evaluation (SMCE) are required to validate the PGIS maps. The number of criteria used by the local experts in drawing the grazing intensity maps seems to influence classification uncertainty. The EBF values for the maps showed that classification uncertainty was less when one criterion was used than when using more than one. Applying spatial multiple criteria tools may be a viable approach to synthesizing the different criteria. The comparison of the grazing intensity map obtained from the local experts with the grazing suitability index map developed using SMCE showed that the higher the grazing intensity class, the higher the grazing suitability index, suggesting that local experts had considerable capability in the identification and application of mapping criteria. This finding may need further investigation since a weak correlation was shown between the grazing intensity map and a grazing suitability index ($r = 0.35$ ($P < 0.01$)). The weak correlation suggests that criteria identification and evaluation may have been difficult for the local experts.

The maps with the lowest uncertainty were based on the composition of palatable vegetation species as the mapping criterion. This suggests that this criterion can be used for mapping grazing intensity because it is associated with measures of forage condition such as ground cover, and quality, but may be limited in use if species

composition and vegetation quantity are not integrated. The definition of grazing intensity may, therefore, be based on the level of livestock grazing use and its impacts on vegetation parameters such as species composition, ground cover, quantity and quality, which can be estimated efficiently using hyperspectral remote sensing. Future research should therefore investigate how local pastoralists and local rangeland experts may participate in applying such a definition and a corresponding proposition for EBF evaluation.

To sum up this study, we conclude that hyperspectral remote sensing, GIS and PGIS are complementary in investigating the mapping and understanding of Mediterranean livestock grazing intensity and vegetation. Based on contiguous narrow band channels within and beyond the visible portions of the spectrum, the high spectral resolution sensor provides detailed information about various vegetation parameters affected by defoliation and competitive interactions among forage plants. If scaled up to field level, efficient monitoring of the growth and competitive ability of various forage species can be achieved. This will help in better understanding of conditions and spatial patterns of herbivore forage. On the other hand, local people perceive broad classes of grazing intensity based on a few criteria and this information may be used as baseline for empirical research including that based on hyperspectral remote. Future research should investigate further the integration and application of the different geo-spatial information technologies and different kinds of knowledge for rangeland studies and management.

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References

Author's Biography

Jane Bemigisha was born on 28th April 1963, in Nyakishenyi Sub-County, Rukungiri District, in south-western Uganda. She attended primary education at Nyakishenyi Integrated Primary School and went to Immaculate Heart Girls Secondary School, Nyakibale and later Trinity College Nabbingo for O' and A' level, respectively. In 1989 she graduated at Makerere University, Kampala, with a Bachelor's Degree in Arts (Geography: 1:1) majoring in Landuse and resources assessment/applied climatology.



After graduation in 1989, she started working as an Environment Officer/Geographic Information Systems (GIS) Analyst and later as Geographic Information Systems/Remote Sensing Specialist with the Ministry of Natural Resources and National Environment Information Center/Environment Management Authority of Uganda (1991 - 1996). In 1995, she undertook a UNEP internship in approaches to Environmental Information Systems (EIS) facility management and Geographical Information Systems (GIS) applications" at Eros Data Centre, Sioux Falls, SD and Blackland Agricultural Research Centre, Temple, Texas, USA.

Between 1996 and 1998, she proceeded with her MSC in environmental systems monitoring and analysis at ITC in The Netherlands, graduating with Distinction. On completion of her MSC, she undertook various environmental consultancies before regular employment as wildlife protected area planner (1998 - 2003), on the USAID Conserve Biodiversity for Sustainable Development (COBS) Project contracted through Associates in Rural Development Inc., and Uganda Wildlife Authority. While planning for wildlife areas, she also lectured, part time, in Rural Landuse Planning at the Department of Geography, Makerere University.

In 2004, she returned to ITC to undertake a PhD research with the Biodiversity Monitoring and Carbon Sequestration in Fragmented Landscapes using Hyperspectral Remote Sensing (BIOFRAG), Department of Natural Resources in conjunction with the Resource Ecology Group, Wageningen University, The Netherlands. Special activities undertaken during the PhD study included serving on the interim executive committee for the International Association of Landscape Ecologists (IALE) Africa Chapter and chairing special sessions for the Chapter during the IALE 2007 conference. She also

developed and delivered a tailor-made course in GIS and remote sensing to post-doctoral research fellows of the Nile Basin Research Programme at Bergen University, Norway.

She is currently employed by the Wildlife Conservation Society as a Geographic Information Systems/Landuse Planning Manager for the USAID Wildlife, Landscapes and Development for Conservation (WILD) programme for Northern Uganda. One of the special assignments is to develop a tailor-made trainers' course for Gulu University staff as trainers of Local Government Officials in Environment Action Planning using geo-spatial information for Post-Conflict areas of Northern Uganda.

ITC Dissertation list

A list of ITC dissertation can be found in:

http://www.itc.nl/research/phd/phd_graduates.aspx

PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 22 credits (= 32 ECTS = 22 weeks of activities)



Review of Literature (5.6 ECTS)

- Mapping and modelling vegetation interactions with grazing (2004)

Writing of Project Proposal (7.0 ECTS)

- Spatial interactions of vegetations and grazing in a Mediterranean area (2004)

Post-Graduate Courses (5.6 ECTS)

- Spatial and temporal aspects in resource ecology; PE&RC (2005)
- Hyperspectral remote sensing data handling using ENVI and IDL programming; ITC (2006)
- Land Science: bringing concepts and theory into practice, using cases in land degradation, payment for environmental services and land restitution analysis and modelling for Bergaville, Kwazulu Natal, South Africa; PE&RC, University of Wageningen and University of Natal, Pietermaritzburg, South Africa (2007)

Competence Strengthening / Skills Courses (2.8 ECTS)

- Scientific writing for non-native English speakers; ITC (2006)
- Presentation skills; ITC (2006)

Discussion Groups / Local Seminars and Other Scientific Meetings (4.8 ECTS)

- PhD tutorials; ITC (2004-2007)
- Resource Ecology; WUR (2005-2006)

PE&RC Annual Meetings, Seminars and the PE&RC Weekend (0.9 ECTS)

- ITC PhD Master class by Jack Dangermond; ESRI (2004)
- ITC Natural Resources day (2005)
- PE&RC day (2006)

International Symposia, Workshops and Conferences (6.0 ECTS)

- 5th African Association of Remote Sensing of Environment; Nairobi, Kenya (2004)
- International Association of Landscape Ecologists (IALE); Wageningen, the Netherlands (2007)

Courses in which the PhD Candidate Has Worked as a Teacher

- Ecosystem modelling (guest lecture); Natural Resources, ITC (1 day)
- GIS and Remote Sensing (guest lectures and analysis support to research fellows); Nile Basin Research Program, Bergen University (30 days)