Pastoral systems and their interaction with spatio-temporal vegetation dynamics in the Atlas Mountains, Southern Morocco

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To whom it may concern

PhD thesis: "Pastoral systems and their interaction with spatio-temporal vegetation dynamics in the Atlas Mountains, Southern Morocco".

I declare that I have reviewed the language of the 'research report' part of the PhD thesis (title above) written by Zakia Akasbi (University of Hamburg) and, as a native speaker, can certify that it is in proper English.

Sincerely

Will Simonson
Cambridge

I dedicate this thesis to the memory of my father

And to my wonderful mother

أهدي هذا البحث إلى روح والدي العزيز رحمه الله و إلى والدتي الغالية

Contents

Abstract

Rangeland degradation is an important issue in ecology and rangeland management, especially in the context of global change. Degradation is particularly severe in arid and semi-arid regions and is caused increasingly by livestock overgrazing. In these fragile ecosystems, rangelands are the main fodder resource for livestock. However, rangeland management strategies are still not sufficiently focused on the prevention of rangeland degradation. Therefore, this research has been conducted in semi-arid southern Morocco to study the two grazing systems occurring in this region – the sedentary and the transhumant – and their interaction with the environment and rangeland productivity.

In the first paper, a study in browsed and unbrowsed permanent plots in a sagebrush steppe was conducted. The interannual variability in standing biomass of the three most dominant dwarf shrubs (*Artemisia herba-alba*, *Artemisia mesatlantica* and *Teucrium mideltense*) was assessed in order to study the effect of browsing on biomass changes. Length, width and height of ten plant individuals from each species were measured to calculate their volumes in each treatment. Power-law regression functions of dry biomass on volume were used to estimate the interannual standing biomass variation from 2004 to 2009. Browsing affected the architecture of the dwarf shrubs and thus different functions for the browsed and unbrowsed plots were found. Moreover, browsing affected the three species differently. While browsing had a negative effect on biomass change of *Artemisia herba-alba*, it had no significant effect on *Artemisia mesatlantica*. *Teucrium mideltense* reacted inconsistently to browsing between the years. The fact that the later two species were only marginally benefited from browsing exclusion could be due to the increased competition of the most dominant species *Artemisia herba-alba*. Interestingly, the standing biomass increased whether or not browsing was excluded, but the increase without browsing was almost double that with browsing. This increase might be due to the recovery of the studied species after a preceding long drought. To generalise the findings of this study, I recommend carrying out others studies on the same species at a larger scale.

In the second paper, the general framework of transhumant migration movements was studied, in addition to the drivers and constraints affecting migration decisions by transhumant pastoralists. For this purpose, the three neighbouring tribes of Ait Mgoun, Ait Toumert and Ait Zekri were selected to conduct an ARGOS tracking study and an interview study. One goat herd within each tribe was tracked for a year, and structured interviews were used to describe the transhumance trajectories of the herders. Four

transhumance types were defined in order to describe migration trajectory length: semi-sedentary (less than 20 km), short-distance transhumance (20–40 km), medium-distance transhumance (40–100 km), and long-distance transhumance (more than 100 km). In all the tribes, different types of transhumance occur and the type of transhumance practised could vary between years within the same tribe and even by the same herder. Ecological and socio-economic factors were influencing transhumant migration. The most important factors that drive migration direction were firstly fodder availability and secondly the harsh climate, which forces the pastoralists to leave the cold high mountains in winter and the hot lowlands in summer. Other factors were herd-specific risk and cost assessment as well as personal constraints of the herdsmen. To conclude, this study provided important knowledge on transhumance in southern Morocco and therefore contributes to a better planning of development and management strategies.

In the third paper, which considers sedentary herds, the seasonal variation of the grazing patterns and intensities of tended goat herds were studied as well as their daily trajectories. For this purpose, one herd from each of the villages Ameskar, Taoujgalt and Bou Skour was selected. A GPS collar was fixed on one goat from each herd to track the movement of its herd for a period of a year. Two different recording intervals, 2 hours and 15 minutes, were used to assess the effect of each on the measured daily walking distance. Grazing intensities were calculated within 4-ha grid cells using ArcGIS. The highest grazing intensities were found in the first 250 m from the stable, while they were very low between 2,000 and 4,000 m from the stable. The seasonal mean daily walking distance varied between 3,480 and 4,460 m. It was longest in summer in Ameskar and Taoujgalt while in Bou Skour it was longest in spring. The shortest distances were in winter and autumn. This variation is mainly driven by fodder availability, climatic conditions, and day length. The relationship between GPS recording interval and the daily distance was explained well by the exponential function. This function allows the extrapolation from longer interval data to the actual walking distances. The decay of grazing intensity with increasing distance was described better with power functions and showed that grazing was concentrated around the stables. According to the results of this study, the area within the first 500 m from the village is the most affected by overgrazing and therefore requires specific management strategies.

In conclusion, the three studies provided insights into important issues related to rangeland management and sustainable land use; i.e. the assessment of rangeland productivity and grazing intensity as well as migration patterns of transhumant herds. Moreover, I estimated a range of carrying capacities in the sagebrush steppe of Taoujgalt:

between 0.34 SSU ha^{-1} in a dry year under continuous browsing and 2.32 SSU ha^{-1} in wet years within the exclosure. The carrying capacity within the exclosure was two to five times higher than outside the exclosure. The actual grazing intensity was nearly 13 times higher than the carrying capacity in the 250 m around the village, while the areas over 1000 m from the village were understocked by sedentary herds. The carrying capacity was strongly influenced by precipitation and rangeland conditions; therefore, it should be adjusted depending on precipitation and fodder availability. Consequently, I recommend doing similar studies within other villages and other tribes in order to complement this thesis and to generalize the findings to a larger scale. Additionally, rangeland managers should take into consideration the estimated carrying capacities in their conservation strategies.

Zusammenfassung

Die Degradierung von Weideland ist in der Ökologie und für nachhaltiges Weidemanagement ein wichtiges Thema, insbesondere im Kontext der Debatte über globalen Wandels. Degradierung ist in ariden und semi-ariden Regionen stärker, und überwiegend durch die Überweidung durch Nutztiere verursacht. In diesen empfindlichen Ökosystemen ist Weideland die wichtigste Quelle der Futterressourcen. Allerdings sind Management-Strategien derzeit noch nicht ausreichend auf die Verhinderung von Degradierung ausgerichtet. Deshalb wurde die hier vorgelegte Studie im südlichen Marokko durchgeführt, um die beiden auftretenden Weidesysteme in dieser Region – sedentär und transhumant – und ihre Auswirkungen auf die Umwelt und die Weideproduktivität in dieser Region zu untersuchen.

Im ersten Paper, wird eine Studie in beweideten und unbeweideten Plots in einer Beifuß-Steppe durchgeführt. Die interannuelle Variabilität der stehenden Biomasse von den drei häufigsten Zwergsträuchern *Artemisia herba-alba*, *Artemisia mesatlantica* und *Teucrium mideltense* wurde untersucht, um die Beweidungsauswirkung auf die Biomasse zu bewerten. Länge, Breite und Höhe von zehn Individuen der drei Arten wurden innerhalb und außerhalb des Zaunes gemessen, um ihre Volumina zu kalkulieren. Exponentielle Regressionsfunktionen von getrockneter Biomasse auf Volumina wurden gefunden. Diese Funktionen in der Folge benutzt für die Einschätzung der Biomassevariabilität von 2004 bis 2009. Die Beweidung hat die Zwergstraucharchitektur beeinflusst. Außerdem war der Beweidungseinfluss zwischen den Arten unterschiedlich. Während Beweidung einen negativen Einfluss auf die Biomasse von *Artemisia herba-alba* hatte, konnte kein signifikanter Einfluss auf *Artemisia mesatlantica* nachgewiesen werden. Der Einfluss auf *Teucrium mideltense* war von Jahr zu Jahr unterschiedlich. Die Tatsache, dass die letzten zwei Arten vom Beweidungsausschluss kaum profitieren ist wahrscheinlich der erhöhten Konkurrenz der dominanten Art *Artemisia herba-alba* geschuldet. Ein weiteres interessantes Ergebnis ist, dass die stehende Biomasse sich unter beiden Treatments (mit und ohne Beweidung) erhöht hat, der Anstieg ohne Beweidung aber fast doppelt so hoch war wie mit Beweidung. Dieser Anstieg könnte durch die Erholung der untersuchten Arten nach einer vorangegangenen langen Dürreperiode bedingt sein. Um die Ergebnisse meiner Studie zu verallgemeinern, empfehle ich die Durchführung vergleichbarer Studien in einer größeren Region.

Im zweiten Paper wurde der allgemeine Rahmen der transhumanten Migrationsbewegungen untersucht, zusätzlich zu den Faktoren und Zwängen, die die

Migrationsentscheindungen der transhumanten Herdenbesitzer beeinflussen. Zu diesem Zweck wurden die drei benachbarten Stämmen der Ait Mgoun, Ait Toumert und Ait Zekri ausgewählt, um eine ARGOS Tracking Studie und eine Interview Studie durchzuführen. Eine Ziegenherde jedes Stammes wurde für ein Jahr mit einem Argos Sender verfolgt und strukturierte Interviews wurden verwendet, um die Wanderbewegungen der Hirten zu beschreiben. Semi-sedentäre Wanderungen (weniger als 20 km vom Wohnort entfernt), Kurzstrecken-Transhumanz (20-40 km), Mittelstrecken-Transhumanz (40-100 km), und Langstrecken-Transhumanz (mehr als 100 km). In allen drei Stämmen treten verschiedene Arten von Transhumanz auf und die Art der Transhumanz, die praktiziert wird, kann sich zwischen den Jahren innerhalb des gleichen Stammes und sogar beim gleichen Hirten ändern. Ökologischen und sozio-ökonomische Einflussfaktoren beeinflussen die Wanderungsentscheidungen der Hirten. Die wichtigsten Faktoren waren erstens die Verfügbarkeit des Futters und zweitens das Klima, das die Hirten zwingt, die kalten Hochgebirge im Winter und die heißen Tiefebenen im Sommer zu verlassen. Andere Einflussfaktoren betreffen spezifische Risiken für die Herden, die Einschätzung der Wanderungskosten sowie persönliche Lebensumstände der Hirten. Diese Studie erbrachte wichtige Erkenntnisse über die Transhumanz im Südlichen Marokkos und kann damit zu einer besseren Planung von weidewirtschaftlichen Entwicklungs-und Management-Strategien beitragen.

Im dritten Paper über sesshafte Herden wurden die jahreszeitlichen Änderungen der Beweidungsmuster und -intensitäten von Ziegenherden sowie ihre täglichen Weidegänge untersucht. Zu diesem Zweck wurde eine Herde aus jedem der drei Dörfer Ameskar, Taoujgalt und Bou Skour ausgewählt. auf Einer Ziege aus jeder Herde wurde mit einem GPS-Halsband ausgerüstet, um die Bewegung ihrer Herde für einen Zeitraum von einem Jahr zu verfolgen. Zwei unterschiedliche zeitliche Auflösungen, 2 Stunden und 15 Minuten, wurden verwendet, um die Wirkung der GPS-Auflösungen auf die kalkulierte tägliche Wanderungsstrecke zu bewerten. Beweidungsintensitäten wurden mit ArcGIS auf der Grundlage von 4-ha Gitterzellen berechnet. Die höchsten Beweidungsintensitäten wurden in den ersten 250 m vom Stall gefunden, während sie in Entfernungen zwischen 2000 und 4000 m vom Stall sehr niedrig waren. Die jahreszeitlich durchschnittliche tägliche Strecke des Weidegangs variiert zwischen 3480 und 4460 m. Sie war in Ameskar und Taoujgalt im Sommer am längsten, während sie in Bou Skour im Frühjahr am längsten war. Die kürzesten Weidegänge fanden sich im Herbst und Winter. Dieser Unterschied wird vor allem durch die Verfügbarkeit des Futters, klimatische Bedingungen, und die Tageslänge erklärt. Die Beziehung zwischen GPS-Auflösung und der täglichen Strecke des Weideganges wurde durch eine Exponentialfunktion erklärt.

Diese Funktion ermöglicht die Extrapolation von längeren zeitlichen Intervallen der Positionsdaten auf die tatsächlich zurückgelegten Strecken. Die Abnahme der Beweidungsintensität mit zunehmender Entfernung vom Stall wurde besser mit Potenzfunktionen beschrieben und zeigte, dass die Beweidung direkt rund um die Ställe stark konzentriert ist. Nach den Ergebnissen dieser Studie ist das Gebiet innerhalb eines Radius von 500 m um das Dorf am stärksten durch Überweidung betroffen und benötigt daher spezifische Management-Strategien.

In ihrer Gesamtheit geben die drei Studien Antworten auf wichtige Fragen im Zusammenhang mit Weideland und nachhaltiger Landnutzung in Südmarokko, insbesondere in Bezug auf die Bewertung der Weidelandproduktivität und Beweidungsintensität sowie auf Migrations-Muster der transhumanten Herden. Abschließend habe ich die Daten der Einzelstudien genutzt, um die Tragfähigkeit der Beifuß-Steppe von Taoujgalt schätzen. Die Tragfähigkeit lag zwischen 0,34 SSU ha^{-1} in trockenen Jahren unter kontinuierlich Beweidung und 2,32 SSU ha^{-1} in nassen Jahren bei Weideausschluss (SSU = *small stock unit* = Kleinvieheinheit). Die Tragfähigkeit im ausgezäunten Bereich war zwei- bis fünfmal höher als außerhalb des Zauns. Die tatsächliche Beweidungsintensität in den 250 m rund um das Dorf war fast 13-mal höher als die Tragfähigkeit, während die Flächen in über 1000 m Entfernung vom Dorf „unterbeweidet“ waren. Die Tragfähigkeit wurde stark vom Niederschlagsgeschehen und dem Zustand des Weidelandes beeinflusst. Daher sollte die Tragfähigkeit nicht als eine fixe Größe betrachtet, sondern fallspezifisch berechnet werden. Diese Daten sollten Weidelandmanager dann bei der Festlegung des Flächenmanagements berücksichtigen. Ergänzend empfehle ich, ähnliche Studien in anderen Dörfern und Stammesgebieten der Region durchzuführen, um die Verallgemeinerung der Ergebnisse für ein größeres Gebiet zu erlauben.

Résumé

La problématique de la dégradation des terrains de parcours constitue une menace réelle aux systèmes écologiques et à l'aménagement des pâturages. Cette problématique s'accentue avec le changement global. La dégradation des terrains de parcours est plus marquée dans les régions arides et semi-arides. Elle est due principalement au surpâturage. Dans ces écosystèmes fragiles, les parcours constituent la ressource fourragère incontournable pour le bétail. Pourtant, les stratégies d'aménagement de ces parcours ne sont pas pour autant satisfaisantes. Par le sujet, la présente recherche a été conduite au Sud du Maroc afin d'analyser les deux modes de pâturage – sédentaire et transhumant – fréquents dans la zone et évaluer leurs interactions avec la productivité des terrains de parcours. Cette recherche a fait objet de trois articles:

Article 1: Etude des placettes de mesure pâturées et autres mises en défens.

L'objet de ces mesures est d'évaluer la variabilité interannuelle de la biomasse sur pied de trois espèces ligneux bas dominantes dans la steppe d'armoise; *Artemisia herba-alba*, *Artemisia mesatlantica* et *Teucrium mideltense* afin d'apprécier l'effet du pâturage sur les changements de la biomasse. La méthode suivie consistait à mesurer, au sein des placettes (pâturées et mises en défens), la longueur, la largeur et la hauteur de dix individus de chaque espèce puis calculer leurs volumes correspondants. Ces données ont été traitées par les fonctions de loi de puissance de la biomasse sèche sur le volume des individus des plantes. Ces fonctions ont été utilisées pour estimer la variation interannuelle de la biomasse de 2004 à 2009. L'interprétation des résultats de ces fonctions nous a permis de constater que le pâturage a affecté l'architecture des ligneux bas et par conséquent différentes fonctions pour les parcelles pâturées et non-pâturées ont été produites. Cette affectation ne suit pas la même tendance chez les trois espèces. Le pâturage a eu un effet négatif sur le changement de la biomasse d'*Artemisia herba-alba*, mais n'a eu aucun effet significatif sur *Artemisia mesatlantica*. La réaction de *Teucrium mideltense*, a varié en fonction des années. Le constat pourrait se justifier pas la concurrence de l'espèce la plus dominante *Artemisia herba-alba*.qui a réduit les chances des deux autres espèces de bénéficier de la mise en défens. Un autre résultat intéressant est que la biomasse sur pied des trois espèces a augmenté avec ou sans pâturage. L'augmentation sans pâturage était presque deux fois plus élevée qu'avec pâturage. Cette augmentation pourrait être due à la reprise des espèces étudiées après une longue période de sécheresse. Pour généraliser les conclusions de cette étude, nous recommandons la conduite d'autres études approfondies sur les mêmes espèces à plus grande échelle.

Article 2: Etude du cadre général des mouvements migratoires des transhumants et les facteurs et contraintes affectant leur décision de migration.

Pour cette fin, nous avons sélectionné trois tribus voisines; Ait Mgoun, Ait Toumert et Ait Zekri. Ces trois tribus ont fait objet d'étude menée avec les colliers ARGOS complétée par une étude d'enquêtes réalisée par nous-mêmes. Le processus de l'étude consistait, d'une part à identifier et suivre un troupeau de chèvre dans chaque tribu pendant un an et d'autre part à remplir des questionnaires structurées pour décrire les trajectoires de transhumance. Quatre modes de transhumance ont été distingués: semi-sédentaire (moins de 20 km), transhumance à courte distance (20-40 km), transhumance à moyenne distance (40-100 km), et transhumance à longue distance (plus de 100 km). Les quatre modes de transhumance existent au sein des trois tribus. La dominance de l'un ou l'autre varie entre les années, au sein de la même tribu et chez l'éleveur lui-même. Plusieurs facteurs écologiques et socio-économiques influencent la décision de migration des transhumants. La disponibilité du fourrage et le climat rigoureux qui oblige les éleveurs à quitter les hautes montagnes froides en hiver et les plaines chaudes en été constituent les deux facteurs majeurs. En outre, les éleveurs prennent en considération le risque de perte du troupeau (cas de maladies) et les coûts de transhumance, ainsi que leurs contraintes personnelles et familiales. Pour conclure, cette étude a réalisé des constats intéressants sur les mouvements de transhumance au sud du Maroc et qui peuvent contribuer à une meilleure planification des stratégies de développement et d'aménagement des parcours.

Article 3: Etude des modes et intensité de pâturage des troupeaux de chèvres sédentaires, ainsi que leurs trajectoires quotidiens.

Un troupeau au niveau de chaque village Ameskar, Taoujgalt et Bou Skour a été identifié. Par la suite, nous avons fixé un collier GPS sur une chèvre au sein de chaque troupeau afin de suivre ses mouvements et ceux de son troupeau pendant une année. Deux intervalles d'enregistrement différents (2 heures et 15 minutes) ont été utilisé et ont permis d'évaluer l'effet de l'intervalle d'enregistrement sur la distance quotidienne parcourue. L'intensité de pâturage dans des cellules de 4 ha a été calculée à l'aide du logiciel ArcGIS. Suite à l'analyse de la variation saisonnière des intensités de pâturage et les trajectoires quotidiennes des chèvres nous avons enregistrées qu'elles sont plus élevées dans les premières 250 m des étables et plus faibles entre 2000 et 4000 m de l'étable. La distance moyenne quotidiennement parcourue a varié entre 3480 et 4460 m. les distances les plus longues ont été parcourues en été à Ameskar et Taoujgalt et au printemps à Bou Skour. Les distances les plus courtes étaient parcourues en hiver et en automne. Cette variation est due principalement à la disponibilité du fourrage, les conditions climatiques, et la longueur de la journée. La relation entre l'intervalle d'enregistrement du GPS et la distance quotidienne a été bien expliquée par la fonction exponentielle. Cette fonction permet l'extrapolation des données de grand intervalle aux distances réelles parcourues. La diminution de l'intensité du pâturage avec la distance a été décrite mieux avec des fonctions de puissance et montre que le pâturage a été agglutiné autour des étables. D'après les résultats ce cette étude, la zone située dans les premières 500 m du village est la plus touchée par le surpâturage et par conséquent, elle nécessite plus de conservation et de stratégies d'aménagement.

En résumé, les trois études ont répondu aux questions importantes liées à la gestion des pâturages et à l'utilisation durable des terres; telles que l'évaluation de la productivité des parcours et l'intensité du pâturage et l'analyse des mouvements migratoires des troupeaux transhumants. Elles ont permis de déterminer un intervalle de la capacité de charge de la steppe d'armoise à Taoujgalt. La capacité de charge a varié entre 0,34 unités de petit bétail par hectare dans une année sèche sous pâturage continu et 3,32 unités de petit bétail dans des années pluvieuses dans la mise en défens. La capacité de charge dans la mise en défens a été deux à cinq fois plus élevée qu'à l'extérieur. L'intensité du pâturage est presque 13 fois plus élevée que cette capacité de charge dans les 250 m autour du village, tandis que les zones à plus de 1000 m du village étaient sous-pâturées par les troupeaux sédentaires. La capacité de charge était fortement influencée par les précipitations et les conditions du parcours. Par conséquent, elle ne doit pas être considérée comme un chiffre fixe, mais ajustée en fonction des précipitations et de la disponibilité du fourrage. Les responsables d'aménagement des pâturages doivent prendre en considération les capacités de charge fournie dans leurs stratégies de conservation des terres de parcours. Afin de compléter la présente étude et de généraliser les résultats à plus grande échelle, il est recommandé de faire des études similaires dans d'autres villages et d'autres tribus.

ملخص

إن إشكالية تدهور المراعي، خاصة مع التغير المناخي العالمي، أخذت اهتماما بالغا في علم البيئة وحماية المراعي. وتزداد حدة هذه الإشكالية في المناطق الجافة وشبه الجافة، كما يساهم الرعي الجائر في تأزيم الوضعية. ورغم كون المراعي تشكل المصدر الأساسي لعلف المواشي داخل هذه النظم البيئية الهشة فإن مخططات استصلاح هذه المراعي لاتزال دون المستوى. في نفس السياق، يندرج البحث الحالي الذي أنجز بجنوب المغرب والذي اهتم بدراسة نظامي الرعي المستقر وشبه المترحل في المنطقة وتفاعلهما مع البيئة وإنتاجية المراعي.

البحث الأول: تتبع نمو النباتات في سهوب الشيح

لهذا الغرض تم تحديد قطع أرضية صغيرة تضم قطعا خاضعة للرعي وأخرى محمية وذلك من أجل تتبع نمو النباتات فيها بصفة مستمرة. بعد ذلك قمنا بتقييم تغيرات الكتلة الحيوية للشجيرات الثلاث الأكثر انتشارا في المنطقة *Artemisia herba-alba*،*Artemisia mesatlantica* و *Teucrium mideltense* من أجل دراسة تأثير الرعي على كتلتها الحيوية. حيث قمنا بقياس طول وعرض وارتفاع عشرة شجيرات من كل نوع لحساب أحجامها في المحمية وخارجها. ثم تمكنا من حساب تغيرالكتلة الحيوية من سنة 2004 إلى 2009 عن طريق دوال القوة بين الكتلة الحيوية الجافة للشجيرات وأحجامها. من أهم نتائج هذه الدراسة تبين أن الرعي يؤثر على بنية الشجيرات . علاوة على ذلك وجدنا أن الرعي يؤثر بشكل متفاوت على الشجيرات الثلاثة. حيث أن الرعي كان له تأثير سلبي على الكتلة الحيوية ل *Artemisia herba-alba*ولم يكن له تأثير واضح على *Artemisia mesatlantica*. بينما كان تأثير الرعي على *Teucrium mideltense* متغيرا بين السنوات. ويمكن تفسير الاستفادة الضعيفة للنوعين الأخيرين من عدم الرعي بزيادة المنافسة لهما من أكثر الأنواع انتشارا *Artemisia herba-alba*. النتيجة الأخرى المثيرة للاهتمام هي أن الكتلة الحيوية ارتفعت سواء بوجود أو بدون وجود رعي. هذه الزيادة تمت بمقدار ضعفين داخل المحمية مقارنة مع خارجها. قد تكون هذه الزيادة نتيجة لانتعاش النباتات بعد جفاف السنوات السابقة. لتعميم نتائج هذه الدراسة، نوصي بالقيام بدراسات أخرى على نفس الشجيرات على نطاق أوسع.

البحث الثاني: دراسة الإطار العام لهجرة الرعاة الرحل والعوامل التي تؤثر على قرارهم بالهجرة

لهذا الغرض،قمنا باختيار قطيع واحد من كل من القبائل المتجاورة الثلاث قبيلة آيت مكون وقبيلة آيت تومرت وقبيلة آيت زكري وأجرينا دراسة باستعمال أطواق العنق ARGOS

(Advanced Research and Global Observation Satellite)

اخترنا معزة واحدة من كل قطيع و تتبعنا حركة القطعان لمدة سنة. كما قمنا أيضا باستجواب الرعاة لتتبع تحركات هجرتهم وفهم العوامل الكامنة وراء قراراتهم بالهجرة. لتحديد طول طريق هجرة الرعاة، حددنا أربعة أنواع من الأنظمة. نظام شبه مستقر حينما يكون مسار الهجرة أقل من 20 كيلومترا ونظام هجرة قصيرة المسافة من 20 إلى 40 كلم ، ونظام هجرة متوسطة المسافة من 40 إلى 100 كلم ونظام هجرة طويلة المسافة أكثر من 100 كلم. بتشخيص هذه الأنظمة داخل القبائل، وجدنا انها تتبع مختلف أنواع الهجرة كما أن نوع الهجرة يمكن أن يتغير بين السنوات داخل القبيلة نفسها و حتى بالنسبة لنفس الراعي. وجدنا أن العوامل التي تؤثر على هجرة الرعاة إما بيئية أو إجتماعية أوإقتصادية. من أهم تلك العوامل توفر الأعلاف في المراعي والظروف المناخية القاسية التي تفرض على الرعاة مغادرة الجبال العالية

الباردة في الشتاء والسهول الشديدة الحرارة في الصيف. إضافة إلى المخاطر التي قد يتعرض لها القطيع وتكاليف الهجرة، فضلا عن الظروف الشخصية للراعي. وللخلاصة فإن هذه الدراسة تقدم معلومات هامة حول هجرة الرعاة في جنوب المغرب ويمكنها أن تساهم في تحسين التخطيط لاستراتيجيات التنمية وإصلاح المراعي.

البحث الثالث: الرعي المستقر، دراسة أنماط وشدة رعي قطعان الماعز إضافة إلى تحديد مساراتها اليومية

لهذا الغرض، اخترنا قطيعا واحدا داخل كل من القرى التالية: أمسكاروتاوجكالت و بوسكور.حيث قمنا بتثبيت طوق GPS (Global Positioning System) على معزة واحدة من كل قطيع لتتبع حركة القطيع لمدة سنة. قمنا خلالها باختيار فترتي تسجيل GPS مختلفتين وهما فترة ساعتين وفترة 15 دقيقة لتقييم تأثير الفاصل الزمني للتسجيل على مسافة المشي المحسوبة يوميا. بعد حساب شدة الرعي في خلايا مساحتها 4 هكتارات باستخدام نظام المعلومات الجغرافية ArcGIS، درسنا التغير الموسمي لشدة الرعي والمسارات اليومية للماعز.وقد أسفرت النتائج على أن أعلى شدة للرعي في 250 متر الأولى من الحظيرة، في حين أن شدة الرعي كانت منخفضة جدا بين 2000 و 4000 متر من الحظيرة كما أن المسافة اليومية التي يمشيها الماعز تراوحت بين 3480 و 4460 متر. وقد سجلت أطول المسافات خلال فصل الصيف في أمسكار وتاوجكالت بينما كانت أطول مسافة مسجلة في بوسكور خلال فصل الربيع. أما أقصر المسافات فسجلت في فصلي الشتاء والخريف. ويرجع هذا الاختلاف أساسا إلى مدى توفر العلف، والظروف المناخية، وطول النهار. وقد تم التعبير عن العلاقة بين مسافة المشي اليومية و الفاصل الزمني للتسجيل ب GPS بشكل جيد بواسطة الدالة الأسية. هذه الدالة تسمح لنا باستنتاج مسافة المشي الفعلية من خلال معطيات ذات فاصل زمني طويل. أما انخفاض شدة الرعي مع زيادة المسافة فقد وصفت بشكل أفضل بواسطة دالة القوة وأظهرت تركز الرعي حول الحظائر. وفقا لنتائج هذه الدراسة، فإن المنطقة الموجودة على مسافة 500 متر من القرية هي الأكثر تضررا من الرعي الجائر، وبالتالي فإنها تتطلب المزيد من استراتيجيات المحافظة و الإصلاح.

إجمالا لقد قدمت الدراسات الثلاث إجابات مهمة حول قضايا أساسية متعلقة بإدارة المراعي والاستخدام المستدام للأراضي من قبيل تقييم إنتاجية المراعي وشدة الرعي، فضلا عن أنماط الهجرة لقطعان الرحل.، هذا بالإضافة إلى حساب الحمولة الرعوية في سهوب الشيح التي تراوحت ما بين 0,34 وحدة حيوانية صغيرة (معزة أو خروفا) في الهكتار خلال سنة جافة و تحت رعي مستمر و 2,32 وحدة حيوانية صغيرة في السنوات الرطبة داخل المحمية. و مثلت الحمولة الرعوية في المحمية ضعف إلى خمسة أضعاف مثيلتها خارج المحمية. كما أن شدة رعي القطيع المستقر المطبقة هناك قاربت 13 أضعاف الحمولة الرعوية في المنطقة المتواجدة على مسافة 250 متر من القرية، أما المناطق الموجودة على مسافة أكثر من 1000 متر فشدة الرعي بها ضعيفة. وقد تغيرت الحمولة الرعوية بشدة مع كمية الأمطار وحالة المراعي .لذلك، فإنه لا ينبغي أن تعتبر الحمولة الرعوية قيمة ثابتة ولكن يجب تعديلها اعتمادا على كمية هطول الأمطار وتوافر الأعلاف في المراعي. وفي الأخيرنقترح على المسؤولين عن حماية المراعي أخذ قيم الحمولة الرعوية المحسوبة في هذه الدراسة بعين الاعتبارداخل استراتيجيات الحفاظ على المراعي. ولتعميق هذه النتائج وتعميمها على نطاق أوسع، فإننا نوصي بإنجاز دراسات شبيهة داخل قرى وقبائل أخرى بالجنوب المغربي.

Chapter 1

General Introduction

Dry rangelands play an important role in the subsistence of rural populations and support 50% of the world's livestock (World Resources Institute 2005). However, these rangelands are subject to severe degradation and continuous reduction of their areas. Approximately 15% of dry rangelands were converted to farmland between 1900 and 1950, and this conversion has accelerated in the decades since (World Resources Institute 2005). Likewise, 73% of dry rangelands worldwide are affected by soil degradation (WOCAT & CDE 2009). Overgrazing – defined as continued heavy grazing which exceeds the recovery capacity of the rangeland and leads to its deterioration (Mullahey et al. 2006) – can be considered the main driver of degradation and reduction in long-term productivity of dry rangelands (Todd & Hoffman 1999). Other frequently mentioned causes of degradation include drought, firewood extraction, and the irresponsible use of pastoral plant species for industrial uses such as oil extraction (Le Houérou 1990; Fikri Benbrahim et al. 2004).

In Morocco, dry rangelands suffer a dramatic loss of quality and productivity: 81% are considered as fairly degraded, and 12.5% as strongly degraded (World Bank 2003). The socio-economic and ecological consequences of this are significant (Cuzin 1996; Cuzin 2003) and exacerbated by climate change. From the mid-1970s to the mid-1990s rangeland areas declined by 10% (Abdelguerfi and Laouar 2000) due to conversion to dryland agriculture (Nefzaoui 2002), and forage production on rangelands decreased between 1984 and 1992 from 4.3 to 3.6 billion forage units (FUs). The Moroccan government undertook several initiatives to combat degradation (MADRPM 1999; MADREF 2000); nevertheless their implementation falls short of expectations, partly due to institutional investment constraints on "collective" rangelands and the lack of acceptance of a top-down planning and management approach (Finckh and Kirscht 2008). This situation requires that decision-makers and resource managers look for best management solutions in order to restore the productivity of rangeland ecosystems and thus improve economic conditions for the local communities.

In order to define sustainable rangeland use intensities, the concept of carrying capacity is widely used in rangeland resource management (Scarnecchia 1990). Carrying capacity is defined as the maximum livestock or wildlife population that an ecosystem can support on a sustainable basis (Dijkman 1999). This definition was revised by Scarnecchia (1990) as the optimum number of individuals or units to achieve specific objectives given specified management options. However, the assessment of carrying capacity, which is based on stocking rates (Galt et al. 2000) and fodder production, remains a challenge in arid and semi-arid rangelands due to the high interannual and seasonal variability of plant growth (Cook and Stubbendieck 1986; De Leeuw and Tothill 1990; Gillson and Hoffman 2007; Jahantigh and Pessarakli 2009). Moreover, problems arise due to different approaches being used to assess carrying capacity in management studies. These approaches can be qualitative or quantitative. The qualitative assessment is based on the visual observation of the rangeland by experienced managers and scientists, with grazing intensity being expressed as light, moderate or heavy grazing (Holecheck and Galt 2000).Meanwhile, quantitative assessment approaches use quantitative parameters such as the stocking rate – defined as the number of specific kinds and classes of animals grazing or utilizing a unit of land for a specified time period (animal unit months per area) (Mullahey et al. 2006) – or the percentage of forage utilized to express grazing intensity (Holecheck and Galt 2000). However, all these parameters that express the carrying capacity vary between ecosystems, and between years and seasons in the same ecosystem, due to variations in vegetation production. Thus, what could be considered as heavy grazing in a dry year could be regarded as light grazing in a rainy year. Therefore, for sustainable rangeland management it is important to quantify the production of, and fluctuations in, plant production and thus to assess annual or even seasonal carrying capacities for each ecosystem.

Despite their importance and their degradation, dry rangelands are understudied in southern Morocco. Few studies have addressed the dynamics and resilience of these rangelands and their carrying capacity, which informs appropriate stocking rates, has not been estimated. Thus, I conducted this study in southern Morocco to evaluate the effects of pastoral systems on rangeland production as well as to assess the carrying capacity of these rangelands and their actual grazing intensities.

This thesis is based on three studies and consists of six chapters.

Chapter 4 (paper I) is a study of biomass estimation of the three most dominant dwarf shrubs – *Artemisia herba-alba*, *Artemisia mesatlantica* and *Teucrium mideltense* – in an exclosure experiment over five years in a sagebrush steppe. Its aim was to estimate the interannual variability in standing biomass and thus study the effect of browsing on biomass production by comparing browsed and unbrowsed plots. Regression functions of volume on biomass were used to estimate the standing biomass. This paper is published in *The African Journal of Range and Forage Science*.

Chapter 5 (paper II) presents a study of transhumant migration within the three neighboring tribes of Ait Mgoun, Ait Zekri and Ait Toumert in the Atlas Mountains. Its aim was to describe the grazing trajectories of the transhumant pastoralists belonging to the tribes and to discuss the social and ecological factors influencing their migration decisions. For this purpose, we used ARGOS trajectories and interview data to describe the migration pattern of the transhumant pastoralists. This paper is published in the *Journal of Mountain Science*.

Chapter 6 (paper III) presents a study of three sedentary goat herds in the three villages of Ameskar, Taoujgalt and Bou Skour in southern Morocco. Its aim was to characterize the spatio-temporal grazing patterns and intensities of the three herds and assess their daily grazing distances. For this purpose, one goat was selected from one herd in each village and was tracked for a year using GPS collars to follow the movement of its herd. This paper is under review in *The Rangeland Journal*.

Chapter 2 is an introduction to the study area in southern Morocco. It includes some general information about the rangelands in southern Morocco, and gives information about the location, climate, vegetation types, soils and geology as well as land use types.

Chapter 3 consists of a general discussion of the research. It presents a broader explanation of the three studies and the calculation of the carrying capacity of the sagebrush steppe in Taoujgalt (Figure 2) within and outside the exclosure for rainy years (2007–2009) and a less rainy year (2005). In addition some management recommendations, research perspectives and conclusions are presented.

Chapter 2

Study Area

2.1. General context of the study

This research was conducted within the context of the BIOTA Maroc project (www.biota-africa.com). This project, a co-initiative of scientists at the University of Hamburg and the Institut Agronomique et Vétérinaire Hassan II in Rabat, monitored biodiversity changes on the Saharan fringe of the High Atlas Mountains in southern Morocco. The objectives of BIOTA Maroc were twofold: (1) to use the biodiversity monitoring results to create suitable tools for sustainable land use and resource management under changing environmental and socio-economic conditions; and (2) to develop, together with the Moroccan partners, adequate intervention schemes and knowledge transfer formats for participative resource planning processes at the communal level.

2.2. General location of the study area

The study area is located in Morocco, a country in North Africa with a climate spanning from Mediterranean to Saharan (Figure 1). The country is crossed by four major mountain chains: the Rif Mountains in the north, the Middle Atlas in the centre, and the High Atlas and Anti-Atlas in the south (Figure 1). Rangelands cover more than 60 million ha and constitute 82% of the drylands (Croitoru and Sarraf 2010). These rangelands are the main source of fodder for livestock and contribute to the subsistence of thousands of people (Mahyou et al. 2010).

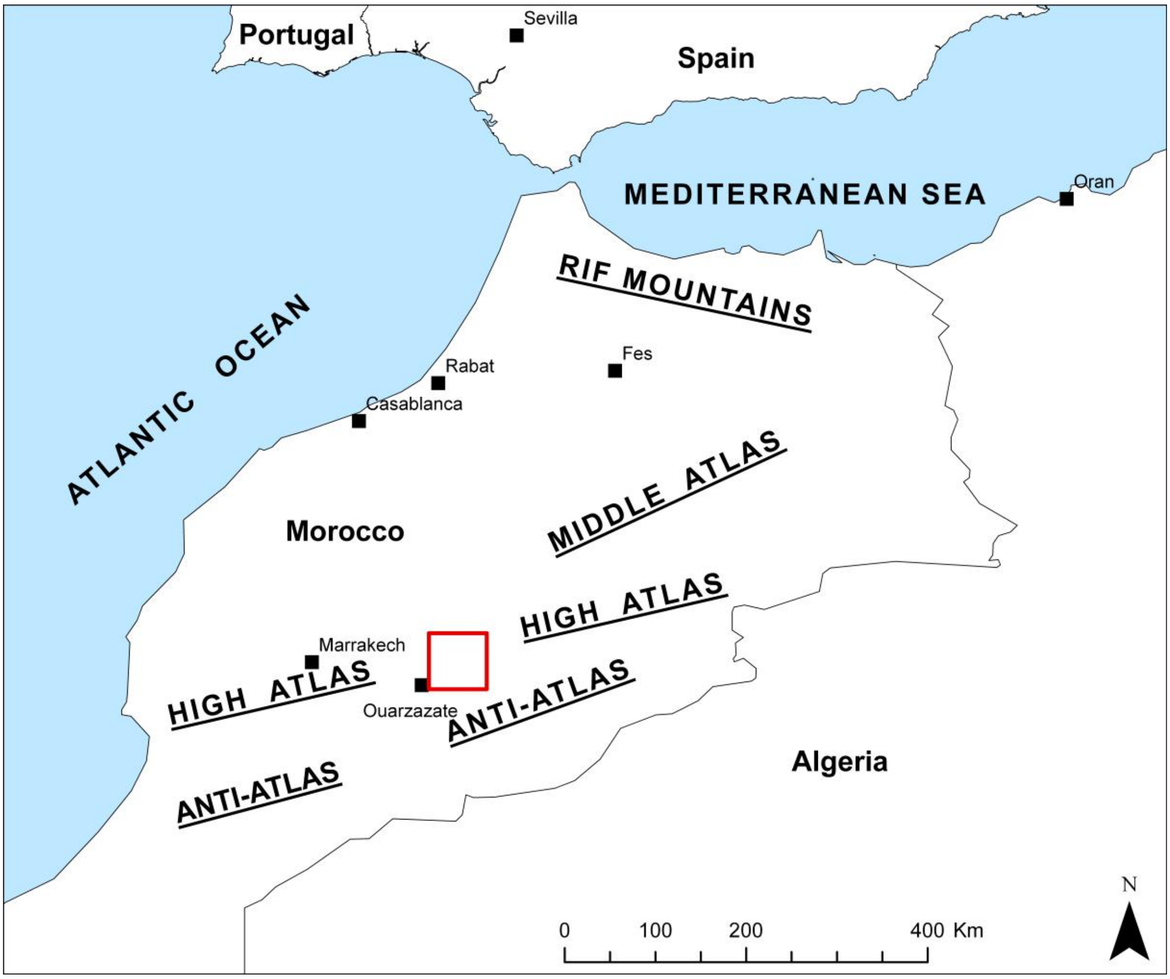

Figure 1. Arrangement of the main mountain chains in Morocco. The red rectangle shows the location of the study area.

2.3. Location of the study area

This study was conducted in the transition zone between the Central High Atlas and the Pre-Saharan Anti-Atlas in southern Morocco (Figure 2). The elevation ranges between 4071 m in the Jebel Mgoun and 1100 m a.s.l. in the Basin of Ouarzazate. The climate in the study area ranges from cold and cool semi-arid in the High Atlas mountains to per-arid cool in the Anti-Atlas with hot and dry summers (Oldeland et al. 2008). The precipitation varies between 600 mm/yr in the summit region of the High Atlas and 110 mm/yr in the Basin of Ouarzazate (Schulz 2008a).

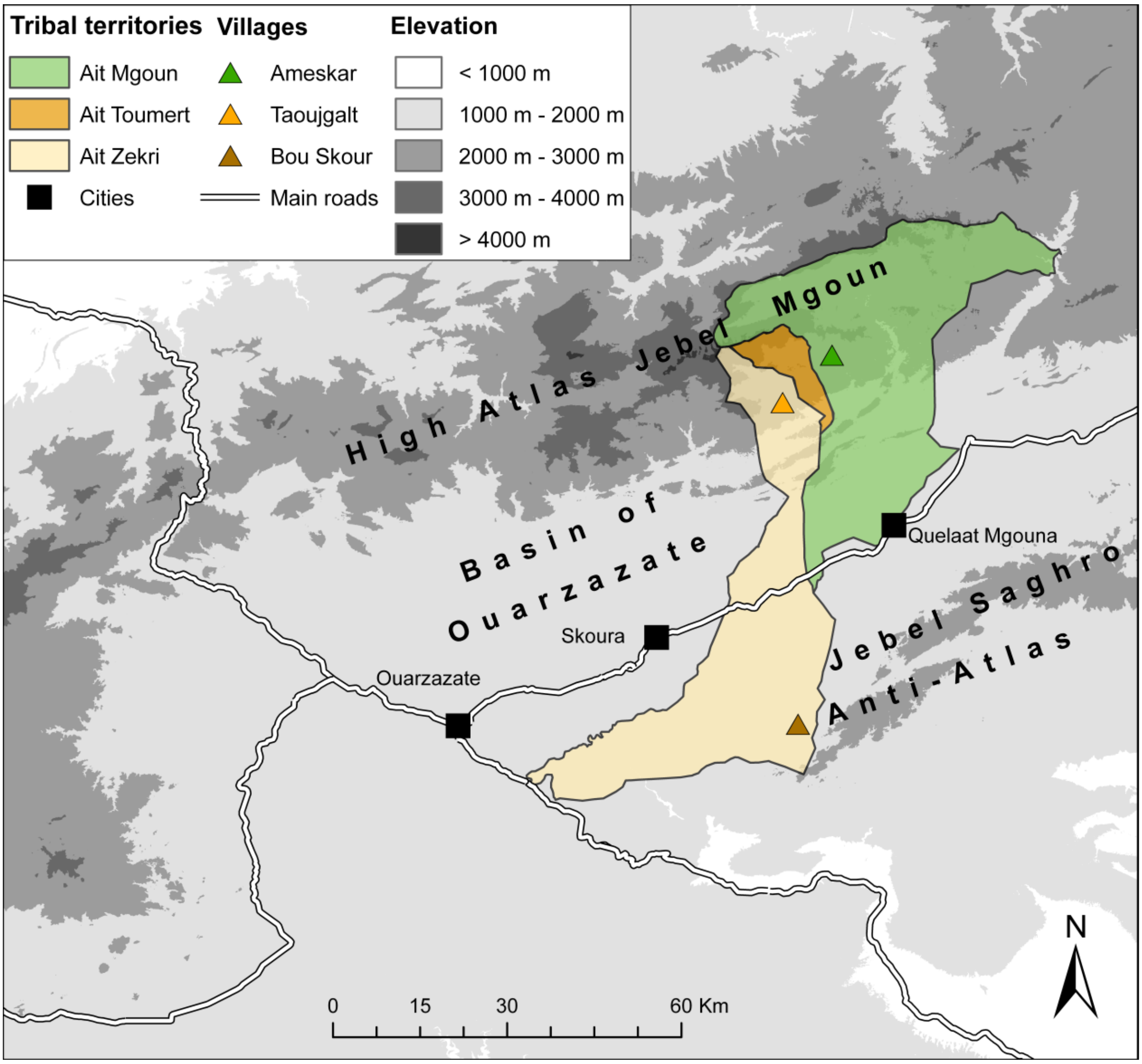

Figure 2. Location of the study area in southern Morocco. Paper I is set in Taoujgalt (chapter 4), paper II in the three tribal territories (chapter 5), and paper III in the three villages Ameskar, Taoujgalt and Bou Skour (chapter 6).

2.4. Vegetation units

The study area comprises different vegetation units (Finckh & Fritzsche 2008): from Oromediterranean high mountain ecosystems with vegetation development in summer, across sagebrush steppes with bimodal vegetation growth in spring and autumn, down to Pre-Saharan steppes and semi-deserts with an ephemeral vegetation development in spring in the Basin of Ouarzazate and in the eastern Anti-Atlas (Jebel Saghro) (Finckh & Poete 2008).

Figure 3. The Oromediteranean ecosystem, test sites of Tichki (left) and Tizi n Tounza (right)

The Oromediterranean ecosystem at high altitudes of the High Atlas (above approximately 2900 m a.s.l.) is dominated by thorny cushion shrubs (Finckh and Poete 2008) such as *Bupleurum spinosum* Gouan, *Alyssum spinosum* L., *Erinacea anthyllis* Link and *Cytisus purgans* Spach (Figure 3). At lower altitudes of down to about 2200 m a.s.l. occurs the Mediterranean Juniper steppe ecosystem dominated by *Juniperus* tree species, *Artemisia* species and *Teucrium mideltense* Humb. (Figure 4). The southern slopes of the High Atlas consist of Ibero-Mauretanian sagebrush steppes dominated by dwarf shrubs such as *Artemisia* species, *Teucrium mideltense* Humb. in addition to different perennial grasses like *Stipa parviflora* Desf. and *Lygeum spartum* L. (Finckh and Poete 2008).

Figure 4. Mediterranean Juniper steppe of the Ameskar test site (left), and the sagebrush steppe of the Taoujgalt test site (right)

Finally, the semi-desert ecosystem from the Ouarzazate Basin to the Jebel Saghro is dominated by dwarf shrubs such as *Convolvulus trabutianus* Schweinf. and Muschl. and *Hammada scoparia* (Pomel) Iljin. (Figure 5).

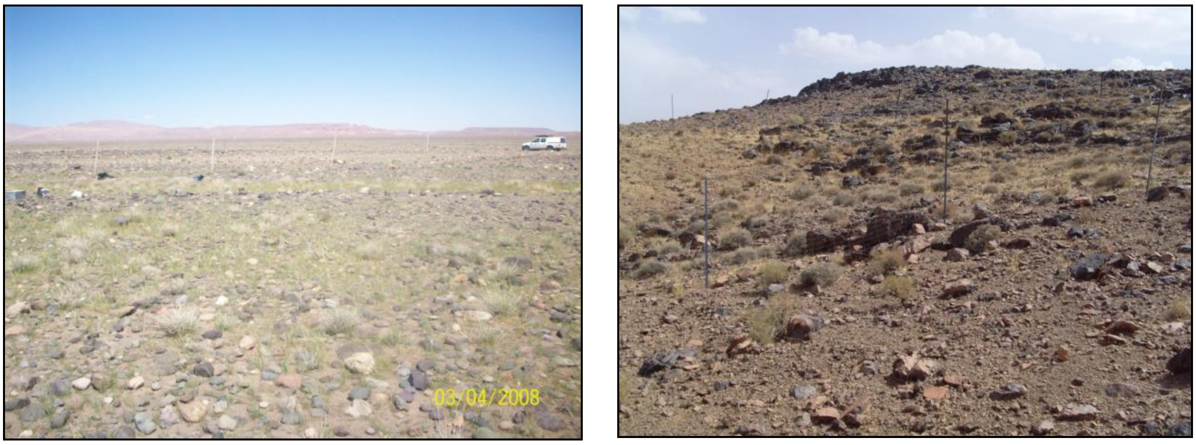

Figure 5. Semi-desert in the basin of Ouarzazate at the Trab Labied test site (left) and in the Anti-Atlas at the Bou Skour test site (right).

2.5. Geology and soils

The study area comprises three main geological units. From north to south they are the High Atlas, the Ouarzazate Basin and the Anti-Atlas. In the High Atlas Mountains as well as in the sediment-filled basins on the fringe of the Saharan Desert, we find a mixture of Mesozoic and Tertiary calcareous and silicate rocks (Menz 2010), while in the Anti-Atlas we find a Proterozoic basement of crystalline bedrocks of Precambrian age with a Paleozoic cover of mainly shallow marine origin (Burkhard et al. 2006; Menz 2010).

The soils in the study area are little developed (Schulz 2008b) and fragile because of their low organic-matter content (World Bank 2003; Klose 2009) and they suffer from water and wind erosion (Croitoru and Sarraf 2010). The most common soil types in the study area are Calcisols, Regosols and Leptosols (Klose 2009). Other predominant types are Luvisols, Fluvisols and occasionally Cambisols, Vertisols and Solonchaks (Miller 2002). In the Anti-Atlas, calcaric Regosols as well as lithic and chromic Leptosols are more common (Weber 2004), interspersed with basaltic outcrops (Schulz et al. 2010). They are characterized by a high skeleton and $CaCO_3$ content, high pH values and partially strong salinity (Klose 2009). Different forms of soil erosion are found in the study area. The slopes exhibit moderate to heavy soil erosion (Miller 2002) with hotspots identified in the high mountain zones (Klose 2009). Higher altitudes are characterized by extensive-linear erosion forms with many rills, while lower altitudes show more linear erosion forms of a higher depth, often deep gullies (Miller 2002).

2.6. Land use types

The most important land use in the study area is pastoralism, mainly of goats, sheep and dromedaries and comprising more than 90% of the area. Sedentary herders share the collectively-owned rangelands with transhumant pastoralist and other mobile users. The use of these rangelands is regulated by traditional and customary rules within and between the different tribes and fractions (Saqalli 2002). Some of the traditional rules or institutions are the Agdals defined as collective pastures with fixed opening and closing dates (Hart 1981). The *Agdal* institution is also very common in other parts of the Moroccan High Atlas and has been studied by many authors (i.e. Mahdi 1999; Aubert et al. 2009; Dominguez et al. 2010). It was shown that the *Agdals* are very important for sustainable use of rangeland and forest resources (Auclair et al. 2011).

The second land use type in the rangeland commons is firewood collection. This activity is practised mainly by women who collect the wood and kindling from shrubs and dwarf shrubs in areas belonging to their village territory (El Moudden 2004). The collected wood is used to satisfy the energy requirements of the local population, mainly for cooking (80%), but also for warming water and heating the house (El Moudden 2004). Another land use type in the study area is irrigated agriculture. This activity is practised mainly in river oases (Menz 2010) and near the villages.

Chapter 3

General Discussion

3.1. Research highlights of the three studies

In this thesis, I worked on the spatio-temporal grazing patterns of sedentary and transhumant pastoralism and their impact on rangeland biomass. The first topic was to estimate biomass variability in an exclosure experiment of the BIOTA Maroc project (www.biota-africa.com), focusing on the sagebrush steppe ecosystem (chapter 4). This study showed that browsing affected the architecture of the dwarf shrubs, and therefore different volume–biomass functions should be used for browsed and unbrowsed plots. Moreover, it showed that browsing affected biomass development of the three dwarf shrubs differently. While browsing showed a significant negative effect on the interannual biomass change for *Artemisia herba-alba*, its effect was not significant for *Artemisia mesatlantica*. For *Teucrium mideltense,* the effect of browsing was inconsistent between the years. In addition, the standing biomass of the three species increased with or without browsing. This increase is probably due to the recovery of the rangelands after a preceding long drought ending in the year 2000 (Born et al. 2008). This notable regeneration effect indicates that short-term exclosures, i.e. up to 5–10 years, could be beneficial for the rehabilitation of these ecosystems.

In a second step, transhumant pastoralism was studied within three neighbouring tribes (see chapter 5). The aim of this study was to outline social and ecological factors influencing migration decisions of transhumant pastoralists. In each tribe, different transhumance types were found, i.e. semi-sedentary pastoralism and short-, medium-, and long-distance transhumance. Migration decisions of the transhumant pastoralists depended on several factors. The most important factors shaping the migration direction were fodder availability and climate. Additionally, individual decisions allow for flexible adaptation within their tribal framework. Other factors were the proximity to members of the larger family, access to markets and risk control. This comprehensive study of migration movements of transhumant pastoralists and the drivers behind their migration decisions may contribute to providing management strategies for dry rangelands.

The third topic was to describe the seasonal patterns of daily trajectories of sedentary herds and assess their grazing intensities using GSP collars (see chapter 6). The grazing intensities were assessed at the level of grid cells of 4 ha. This spatially explicit approach was used for the first time in southern Morocco, contrasting with previous studies, which had only considered the mean grazing intensity within a large area. The highest grazing intensities occurred in the first 250 m from the stable. Generally the herds did not exceed distances of 3000 m from the stables. These results are in line with other studies showing that water points or villages are hotspots for grazing. The mean daily distance and maximum distance from the stable varied significantly between seasons and was driven by fodder availability, temperature and the day-length. In addition, this study provided two new methodological approaches. The first one was a regression function showing the decay of grazing intensity with increasing distance from the stable or village, and the concentration of grazing around the stables. The second one was the relationship between the daily walking distance and the GPS recording interval. This relationship could be useful for other studies because it allows the calculation of the actual walking distance even with long recording intervals. The use of small intervals requires changing the GPS collar battery frequently and this is generally impractical in this kind of field study. These results may be useful for rangeland managers to establish specific management strategies for areas near villages.

The three topics raised in this thesis concern dry rangelands in southern Morocco in terms of biomass production (chapter 4) and pastoral land use (chapter 5 and 6). The estimation of biomass in chapter 4, as well as unpublished data, allow for the estimation of the carrying capacity under different browsing and climatic conditions (see section 3.2). The estimated carrying capacity will then be compared to the grazing intensity assessed in chapter 6. The study of the trajectories of sedentary (chapter 6) and transhumant pastoralists (chapter 5), and the factors influencing their movements could help refine carrying capacity estimation, taking into account varying conditions such as drought, fodder availability, water availability, and thus enabling the settling of proper stocking rates.

3.2. Carrying capacity

The concept of carrying capacity (CC) is widely used to assess land use intensities that allow for sustainable use of rangelands (Sayre 2008). However, this concept has elicited controversial debate and several authors have questioned whether the concept is applicable in ecosystems with high seasonal variation in rainfall and fodder availability (e.g. Dijkman 1999; Cliggett 2001; Sayre 2008). Other critics, like Cliggett (2001), considered that the CC ignores the complexity of the human-environment relationship and De Leeuw & Tothill (1990) criticized the use of CC in sub-Saharan Africa because different authors calculated values of CC differently. These discrepancies were caused by taking different parameters into consideration for the calculation of the CC, including grazing efficiency (the proportion of total herbage livestock can harvest), forage loss (due to trampling, fouling, decomposition, etc.) and the allowable plant utilization percentage, which is the maximum proportion of forage that can be grazed without causing rangeland deterioration (FAO 1991). Moreover, biomass quality and fodder value for livestock are largely ignored in the calculations of CC (De Leeuw & Tothill 1990) despite its influence on the forage intake by grazing livestock (Launchbaugh 2008). However, there are also comments supporting the CC concept. For example McLeod (1997) stated that CC can be a useful tool in ecosystems with low environmental and climatic variability.

Criticism of the use of the CC concept in ecosystems with high seasonal and interannual climatic variability (e.g. the sagebrush steppe ecosystem of Taoujgalt) by some of the above-mentioned authors has mostly referred to the calculation of one single value for a system with a strongly fluctuating productivity. However, our data allow the estimation of a range of CCs for this rangeland under different ecological conditions, and the understanding of this range may contribute to its sustainable management. Therefore, I will estimate the CC range based on calculations under different climatic and browsing conditions. These calculations will allow the definition of the range within which the CC fluctuates for a given studied site.

3.2.1. Calculation of the carrying capacity under browsing for the years (2007–2009)

The carrying capacity can be calculated by dividing the *total usable forage* by the *forage demand*.

Calculation of the total usable forage

The average standing biomass of the three dwarf shrubs *A. herba-alba*, *A. mesatlantica*, and *Teucrium mideltense* in Taoujgalt from 2007 to 2009 was 1106 kg ha^{-1} outside of the exclosure. In terms of edible biomass, it was only 248 kg ha^{-1} (unpublished data). The edible biomass included the leaves and fresh stems and only excluded the woody parts of the plants. This estimation applied the volume–biomass functions to edible biomass values using a similar method based on total biomass in chapter 4. For a sustainable use of the sagebrush rangelands, the allowable plant utilization percentage is between 30 to 40% (Holechek 1988). In the following, I will use 35% as the allowable plant utilization percentage. Therefore:

Total usable forage = edible biomass × utilization percentage = 248 kg ha^{-1} × 35% = 86.8 kg ha^{-1}.

Calculation of forage demand

Forage demand is defined as the total amount of forage consumed by a grazing animal during the grazing period (Holechek 1988). Ruminants on rangelands consume about 2.5% of their body weight per day (Launchbaugh 2008). In the study area, the average body weight of an adult sheep or goat (Small Stock Unit: SSU) is 20 kg (White House 2004). Therefore:

Forage demand = 2.5% × average body weight × 365 = 0.025 × 20 × 365 = 182.5 kg SSU^{-1} $year^{-1}$. This means that 182.5 kg of forage is needed to feed each SSU for one year. Then:

Carrying capacity = total usable forage/forage demand = 86.8 kg. ha^{-1}/ 182.5 kg SSU^{-1} $year^{-1}$.

The *carrying capacity* in the sagebrush steppe of Taoujgalt for the period 2007–2009 was 0.47 SSU ha^{-1}.

Assessment of the grazing intensity

For the same period, I calculated the grazing intensity in Taoujgalt (chapter 6). Within the first 250 m around the village, the grazing intensity was 6.12 SSU ha^{-1} (Table 3). This is nearly 13 times higher than the carrying capacity of these rangelands, as calculated above. The grazing intensity was approximately equivalent to the carrying capacity at distances of 500–1000 m distance from the stable, and even lower grazing intensities occurred in areas more than 1000 m distant from the stable (0.14 SSU ha^{-1}).

However, the grazing intensities calculated in chapter 6 considered only the sedentary herds. If I considered the transhumant herds, the actual grazing intensities would be higher than the values given above. In particular, at higher distances from the village (> 1000 m) there is an increasing overlap with transhumant herds using the same area. This increase in grazing intensities affects mainly the remote areas because the transhumant pastoralists avoid grazing their animals close to the villages in order to avoid competition for forage (see chapter 5). The calculations shows that those remote areas (> 1000 m distance) are underutilized by sedentary herds. The only pastures clearly overgrazed are the direct surroundings of the village of Taoujgalt, i.e. within a radius of 250 m.

The carrying capacity calculated above was based on biomass production during October (2007), May (2008) and June (2009).

These measurements corresponded to three relatively rainy years with an annual precipitation of 289 mm. Therefore, during dry years, biomass production of the three species, and thus the carrying capacity, will be lower. This will be shown for the year 2005 in the same ecosystem (see next section).

3.2.2. Calculation of the carrying capacity under browsing for the year 2005

The edible biomass of the three dwarf shrubs was 177 kg ha^{-1} (unpublished data). Using the same calculation method given above, CC for 2005 = 177 kg ha^{-1} × 35% / 182.5 kg SSU^{-1} $year^{-1}$, therefore:

the *carrying capacity* for 2005 = 0.34 SSU ha^{-1}.

Rainfall in 2005 was 193 mm, representing just 66.8% of the annual precipitation for 2007–2009. As a result, the carrying capacity decreased by 0.13 SSU ha^{-1}, i.e by 27.6%. Whilst 2005 was not an especially dry year, it does show clearly that the carrying capacity has to be adjusted depending on the precipitation and biomass production of the year in question.

3.2.3. Calculation of the carrying capacity within the exclosure

In the exclosure, the edible biomass of the three dwarf shrubs for the relatively wet period of 2007–2009 was 1211 kg ha^{-1} (unpublished data). Thus:

the *carrying capacity* was 1211 kg ha^{-1} × 35% / 182.5 kg SSU^{-1} $year^{-1}$= 2.32 SSU ha^{-1}.

For the comparatively dry year 2005, the edible biomass for the three species was 516 kg ha^{-1} within the exclosure and correspondingly:

the *carrying capacity* was 516 kg ha^{-1} × 35% / 182.5 kg SSU^{-1} $year^{-1}$= 0.99 SSU ha^{-1}.

Table 1. Summary of the carrying capacity results in (SSU ha^{-1}).

Carrying capacity	Inside the exclosure	Outside the exclosure	Proportion (inside /outside)
2005	0.99	0.34	2.91
2007–2009	2.32	0.47	4.94

The carrying capacity inside the exclosure is much higher than outside the exclosure (Table 1). The CC of the Taoujgalt rangelands fluctuates between 0.34 (dry year, pasture in poor condition) and 2.32 SSU ha^{-1} (wet years, pasture in good condition). This example shows how pastoral management that maintains rangelands in good conditions enhances the CC between 2.91 and 4.94 times. The calculation of CC within the exclosure was based on biomass recovery after several (4–9) years. Therefore, short term exclosures of rangelands could subsequently allow for the grazing of more than double the number of animals and thus be an efficient management tool to restore standing biomass and improve rangeland productivity in these areas. Stocking rates should be adjusted flexibly to rangeland conditions with varying climatic conditions, fodder availability, and fodder quality.

3.3. Recommendations for management practices

Rangelands are the main source of animal fodder in the study area, while supplementation is rarely practised: only in the case of severe droughts, or for lactating females during cold winters (White House 2004). During a drought, the pastoralists generally reduce animal numbers by selling them in the market in order to reduce the expensive fodder supply. This reduction of animal number is beneficial for rangeland conservation because it decreases grazing pressure on these rangelands. Moreover, transhumant migration plays an important role in rangeland conservation. In very dry years, the transhumant pastoralists reach far pastures in other provinces searching for fodder resources (chapter 5). Additionally, customary rules, such as the *Agdals*, regulate land use rights between the transhumant pastoralists (see chapter 2) and thus rangelands have time to recover. These rules are evidence of the awareness of the pastoralists of the importance of resource conservation, despite the absence of environmental and ecological education in the region. However, sedentarisation policies applied to transhumant pastoralists, contributed to conversion of rangeland to farmland and thus their degradation (Aït Hamza 2002).

Therefore, I recommend that the local authorities encourage transhumance as opposed to sedentarisation. In addition, development strategies should be a priority in this poor region because the improvement of the living conditions of the population will attenuate population dependence on the resources. This will have a very positive impact on natural resources. Additionally, I recommend that decision-makers and rangeland managers take into consideration the provided carrying capacities (see section 3.2) in their management strategies and to evaluate the impact of carrying capacity on land users, vegetation and soil resources. Moreover, sensitising the local population about sustainable land use would improve their knowledge and have a positive effect on rangeland conservation. Rangeland managers should implement conservation strategies as well as improvement strategies for the rangelands in order to produce more resources to satisfy the feed requirement of the grazing animals in these poor regions.

3.4. Conclusions

In this thesis, I studied animal–vegetation interaction in semi-arid rangelands through biomass production estimation and the analysis of the sedentary and transhumant pastoralism. With this work, I suggest management strategies for rangelands and their sustainable use. The main findings are as follows:

- Browsing exclusion can have a differential effect on the plant species, depending on their dominance and palatability. While browsing had a negative impact on *Artemisia herba-alba*, *A. mesatlantica* and *Teucrium mideltense* hardly benefited from browsing exclusion (chapter 4). This is due to the increased competition of the former species.
- Biomass production could quickly recover in the studied (non-equilibrium) ecosystems. This recovery was observed by biomass increase for the three species after a previous drought. Nevertheless, this increase was higher without browsing (chapter 4).
- The actual grazing intensity was nearly 13 times higher than its carrying capacity near the village of Taoujgalt, i.e. up to 250 m distance (chapter 3 and 6).
- The carrying capacity should be adjusted according to precipitation, fodder availability and fodder quality (section 3.2).
- Sedentary herds graze mostly within 3000 m of their villages (chapter 6), and trajectories vary between seasons.
- Migration movement of the transhumant pastoralists is mainly driven by fodder availability and harsh climate (chapter 5).
- Transhumance could be cancelled by herders when there is a risk of losing the herd, e.g. to disease.

3.5. Research perspectives

Although this research provided important data for rangeland management, it is not sufficient to respond to all the urgent questions in the study area due to its large extent and the complex interaction between the ecological and social conditions. In addition, the carrying capacity calculations are based on an individual plot and exclosure, therefore, their extrapolation to the whole ecosystem would require more research. Thus, I recommend follow-up studies to be carried out in the region in order to complement my work and to extend the findings to a larger spatial and temporal scale. I suggest a number of topics for further studies:

- A study on biomass production along an altitudinal gradient using similar methods used in this study and thus assessing the carrying capacity of the different ecosystems in the region.
- To study the impact of grazing on biodiversity along an altitudinal gradient from the Oromediterraneen ecosystem to the Sahara.
- A study on transhumant movement in the other tribes existing in the region such as Ait Sedrat, Ait Atta, and Imaghrann. For this study, I recommend the use of GPS collars instead of ARGOS collars because the latter were not precise enough, due to signal problems in mountainous terrain.
- A study on the impact of grazing exclusion on soil fertility.
- Estimation of the actual grazing intensities of the rangelands in the study area by including other animal species such as dromedaries, equids and wild animals (rabbits) as well as the grazing intensities of the transhumant herds.

This thesis offers a basis for future studies and contributes to the sustainable use of dry rangelands and their management.

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Chapter 4

Paper I

Volume–biomass functions reveal the effect of browsing on three Moroccan dwarf shrubs

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Research Note

Volume–biomass functions reveal the effect of browsing on three Moroccan dwarf shrubs

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We studied the effects of browsing on the plant architecture and volume-biomass relationships of three dominant dwarf shrubs – *Artemisia herba-alba*, *A. mesatlantica* and *Teucrium mideltense* – in a sagebrush steppe in the Central High Atlas Mountains, southern Morocco. For this purpose, we developed power-law volume-biomass functions based on nonlinear regressions for each of these species, under both browsed and unbrowsed conditions. These functions were then applied to individual-based annual monitoring data from inside and outside a browsing exclosure to calculate standing biomass for each of the years from 2004 to 2009. The biomass of the three species was well predicted by the allometric functions, and different functions for the browsed and unbrowsed conditions reflected changes in plant architecture. Browsing had a significant negative impact on biomass for *A. herba-alba* but not for *A. mesatlantica*, whereas its effects on *T. mideltense* were inconsistent between years. The fact that the latter two species hardly benefited from browsing exclusion might be because of increased competition from the more dominant *A. herba-alba*. During the study period, the standing biomass increased whether or not there was browsing, which might be because of the recovery of the shrubs after a preceding severe drought. Further studies are needed in order to investigate the generality of the findings.

Keywords: allometric function, Atlas Mountains, nonlinear regression, permanent plot, plant architecture, standing biomass

Plant biomass is the most common measure of rangeland production (Cook and Stubbendieck 1986). The assessment of the standing biomass and its fluctuations is crucial in rangeland management. Accordingly, direct and indirect methods have been developed. Direct methods based on biomass harvesting (e.g. Patton et al. 2007) are more precise, but they are laborious, costly and destructive. On the other hand, indirect methods are cheaper, less detrimental to fragile ecosystems, and allow for easy spatial extrapolation of biomass estimates. Namely, methods based on remote sensing (e.g. Kawamura et al. 2003), allometric regression models (e.g. Usó et al. 1997, Paton et al. 2002, Abdelkader et al. 2008), and combinations of these two methods are frequently used. In this context, allometric regression models generally relate dimensional plant data, i.e. measures of height and diameter, to biomass. Such methods are useful; however, as static models, they do not describe the strong fluctuations of biomass production in ecosystems with high seasonal and interannual climatic variability (Le Houérou and Hoste 1977). In consideration of this problem, several studies (Abrams et al. 1986, Xiao et al. 1996) used monitoring methods to follow vegetation changes over several years and combined this approach with some of the previously cited methods.

Southern Moroccan steppic rangelands have been the subject of research on total biomass production (Baumann 2009), but little is known about their species-specific standing biomass, or the interannual changes to this biomass with and without browsing. In this study we aimed to estimate the variability in standing biomass of three dominant dwarf shrubs in an exclosure experiment, using allometric functions.

The study was conducted in a large intramontane basin in the southern ranges of the Central High Atlas Mountains at 31° 23′ N, 6°19′ W and about 1 870 m asl, near the village of Taoujgalt in the province of Ouarzazate, Morocco. The study site is located on the toeslope of a calcareous alluvial cone and is representative for the rolling plains within the basin. The mean annual precipitation from 2001 to 2006 was 238 mm and the mean annual temperature 14.2 °C (Schulz et al. 2010). The climate is characterised by two rainfall peaks in autumn and spring, separated by a short dry winter and a long dry summer. Monthly mean temperatures reach their maximum in July (26 °C) and their minimum in January (5 °C) (Schulz et al. 2010).

The vegetation is a sagebrush steppe dominated by the three dwarf shrub species *Artemisia herba-alba* Asso, *A. mesatlantica* Maire (Asteraceae), and *Teucrium* *mideltense* (Batt.) Humbert (Lamiacae). *Artemisia herba-alba* has two periods of high productivity, at the end of spring and in early autumn, with a maximum biomass in autumn, whereas *T. mideltense* has its peak biomass development between late spring and early summer (Gresens 2006). Perennial grasses play a subordinate role, whereas annual species are well represented in terms of species richness and abundance with many small individuals mainly of the families Poaceae, Brassicaceae and Asteraceae, yet are not important in terms of biomass (Baumann 2009).

Traditionally, the steppes within the basin were managed as summer pastures with restricted access. Currently, the steppe is used throughout the year for browsing by sheep and for firewood extraction, and in some localities for crop farming practised by sedentary people. The sagebrush steppe is in good condition in terms of biomass production and ecological integrity (SENS 2005). The stocking rates vary considerably between seasons. Mahler (2010) found 0.25 small stock units (SSU) ha^{-1} in 2009, whereas Freier et al. (2011) found 0.5 SSU ha^{-1} in early summer of 2009 for the area of the study site. In addition, two short stocking rate peaks occur in early May when many transhumant pastoralists gather in the area with their herds waiting for the opening of the high mountain pasture and in autumn when the herders migrate back to the lowlands.

In early spring 2001, an exclosure experiment of about 1 250 m² was installed within the rangelands of the study site. Two plots of 10 m × 10 m each placed inside and outside the exclosure in sites with similar and representative vegetation and soil conditions. Each plot was divided into a grid of 400 quadratic subplots of 0.25 m². Length, width, and height of all individuals of the three dominant species *A. herba-alba*, *A. mesatlantica* and *T. mideltense* were monitored once per year from 2004 to 2009. As precipitation and productivity in the study area show a bimodal distribution with spring and autumn peaks (Schulz et al. 2010), we shifted the measurements in dry years to autumn in order to capture always the main part of the annual biomass increase. However, in autumn 2006 measurements could not be obtained because of strong thunderstorms that destroyed roads and blocked access to the study area. For this reason, measurements were taken prior to the beginning of the growing period in early spring 2007 and used as a surrogate for the 2006 data.

To establish volume–biomass relationships, we harvested 10 individuals of each species both inside and outside the exclosure in 2008, representing the full size ranges occurring in the respective treatment. Length, width, and height of the harvested individuals were measured in order to calculate the plant volume. After measurement, the aboveground biomass of the individuals was cut, oven-dried at 80 °C for 24 h, and weighed.

For the individual plants, volumes were calculated assuming the shape of a half ellipsoid for all three species with the following formula:

$$V = 1/6\, L W H \pi,$$

where V = volume, L = length, W = width and H = height.

We developed power-law regressions for each species, both inside and outside the exclosure in order to describe the volume–biomass relationships for the measured species. These calculations were based on the spring biomass harvested in 2008. The formula was:

$$B = a V^b,$$

where B = biomass, V = volume, and a and b are fitted parameters.

We chose to model this power law directly with a nonlinear regression approach (Motulsky and Christopoulos 2004) instead of applying log-transformations to both axes and then using a linear regression ($\log B = \log a + b \log V$) as it is frequently done. Our approach with B instead of $\log B$ as the dependent variable gives relatively more weight to the larger individuals, which are more relevant in terms of biomass per area. The regression equations were calculated with the nonlinear regression module of STATISTICA 8.0 (StatSoft 2007). We used the default setting of the program (loss function = $[OBS - PRED]^2$; estimation method = quasi-Newton; convergence criterion = 0.0001; step width for all parameters = 0.5; starting values for all parameters = 0.1).

In order to apply the equations established for 2008 to all years between 2004 and 2009, we assumed that outside the exclosure, overall browsing pressure remained constant at 0.25–0.5 SSU ha^{-1}. Therefore, plant architecture, i.e. canopy shape, should hardly have changed over the years, and thus the same function was assumed valid over the whole period. For the subplots inside the exclosure, two different approaches were applied. The first approach (further referred to as the static method) used the formula established in 2008 for all the years. In the second approach we applied a linear transition (transitional method) between the starting point in 2001, when the exclosure was installed, using the function for the browsed subplots and the function established for the exclosure in 2008, assuming that plant architecture only gradually adapted to the relaxation from browsing pressure (Figure 1). According to this idea, we adopted different equations for the growing biomass in

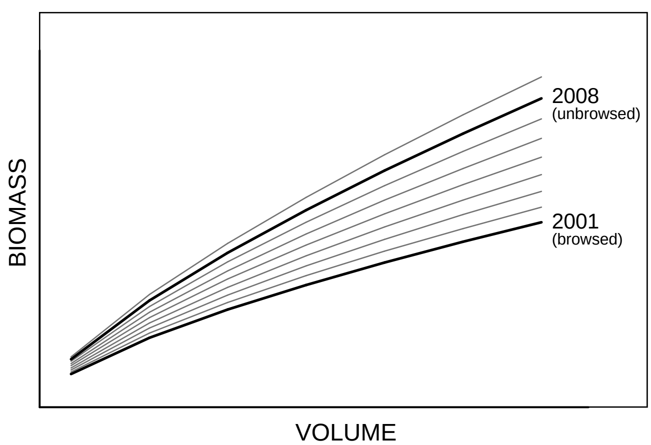

Figure 1: Schematic representation of transitional method for biomass calculation inside of the exclosure. The lower thick curve represents the volume–biomass function outside the exclosure; the upper thick curve shows that inside the exclosure. The curves between these are calculated assuming a linear transition between the two functions

each year. To achieve this, we calculated the difference of the fitted parameters *a* and *b* between the outside formula and the static inside formula. Then we let both parameters change over the years with a constant increment between these endpoints (Figure1).

We used the specific regression functions for species, treatments, and years to estimate the biomass of each of the measured individuals. In the case of the dominant *A. herba-alba*, we used these values to calculate the standing biomass for each of the 0.25 m² subplots. For the two other species, which were only present in a small subset of subplots, we followed the development of the plant individuals separately. For *A. mesatlantica*, we had 25 plants inside and 29 outside, whereas *T. mideltense* was represented by 33 plants inside and 36 plants outside. We displayed the plots and the individual plants in a grid using a GIS to follow the time series in a spatially explicit manner and to correct for position errors. Missing records, i.e. individuals that were overlooked in a certain year, were entered by using the averaged biomass between the previous year and the subsequent year.

In order to test for differences in mean biomass between the browsed and unbrowsed plots and for changes between pairs of subsequent years within each 0.25 m² subplot, we used the permutation-based analogue to a two-sample *t*-test as implemented in the software PAST 1.95 (Hammer et al. 2001) with 10 000 permutations. A permutation-based comparison of means does not require any distributional assumption, as both parametric and non-parametric tests do (Quinn and Keough 2002, Manly 2007). Accordingly, such an approach is well suitable for extremely skewed distributions as in our case. The effect of browsing on biomass changes was evaluated by comparing the plots or individuals of the treatments between all pairs of subsequent years and for the cumulative changes over the five-year study period. As the replication was done only on the level of subplots or individuals, but not at the level of treatments, the case study can mainly address the question of whether and how plant architecture differs between species and treatments, but does not allow for formal inferences about browsing effects in the rangelands of the study region in general (see e.g. Quinn and Keough 2002, pp 158 et seq.).

The biomass of the three study species was well predicted with power-law functions of their volume in both management variants (Figure 2). The regressions explained 67–89% of the variance. The proportions of variance explained within species were similar inside and outside of the exclosure, with the exception of *T. mideltense*, which had a considerably higher R^2 value inside.

Our analyses returned different volume–biomass functions for the species with and without browsing. In the case of *A. herba-alba* (Figure 2a), biomass was higher inside than outside for the same plant volume, which means that the individuals grew more densely without browsing. By contrast, the biomass of *A. mesatlantica* was higher outside of the exclosure (Figure 2b). Finally, for small plants (volume < 5 dm³) of *T. mideltense* (Figure 2c) there was no difference, whereas the biomass per volume of large individuals was higher with browsing.

The static and transitional methods of biomass calculation yielded very similar results for *A. herba-alba* and *T. mideltense*, whereas the patterns found in *A. mesatlantica* strongly differed between these two methods (Table 1, Figure 3). The static method for *A. mesatlantica* indicated no significant differences between the treatments, whereas the transitional method found a negative impact of browsing exclusion on cumulative biomass development of this species over the five years (Table 1).

For *A. herba-alba,* the cumulative biomass from 2004 to 2009 increased strongly both inside and outside the exclosure, but the absolute biomass increase was three-fold higher without browsing (Table 1). Considering the interannual changes, browsing was strongly negative for biomass development in three cases (2005–2006, 2007–2008 and 2008–2009), negative in 2004–2005, whereas it showed inconsistent effects among the two calculation methods for 2006–2007 (Figure 3a).

For *A. mesatlantica*, the cumulative biomass from 2004 to 2009 showed generally a slightly more positive trend with browsing than without (Table 1). For this species, we found the largest differences between our two methods of biomass calculation. We observed a positive trend with and without browsing for the static method. By contrast, a slight negative trend was observed with the transitional method. Furthermore, the difference between the browsed

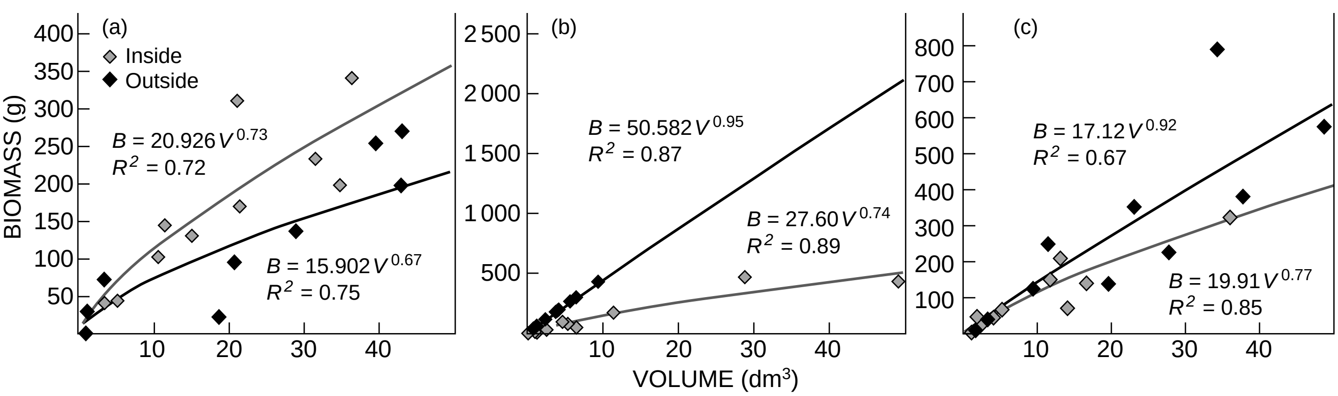

Figure 2: The power-law functions determined with nonlinear regression inside and outside the exclosure for (a) *Artemisia herba-alba*, (b) *Artemisia mesatlantica* and (c) *Teucrium mideltense*. B = aboveground biomass (g), V = volume (dm³)

Table 1: Mean cumulative annual biomass change from 2004 to 2009 in comparison between grazed and ungrazed plots. The mean biomass changes for *Artemisia herba-alba* are given in g m⁻², and those for *A. mesatlantica* and *T. mideltense* in g individual⁻¹

Species	Grazed	Ungrazed (static method)	*P*	Ungrazed (transitional method)	*P*
Artemisia herba-alba	+92	+230	<0.001	+279	<0.001
Artemisia mesatlantica	+61	+56	0.798	–1	0.009
Teucrium mideltense	+11	+17	0.847	+13	0.855

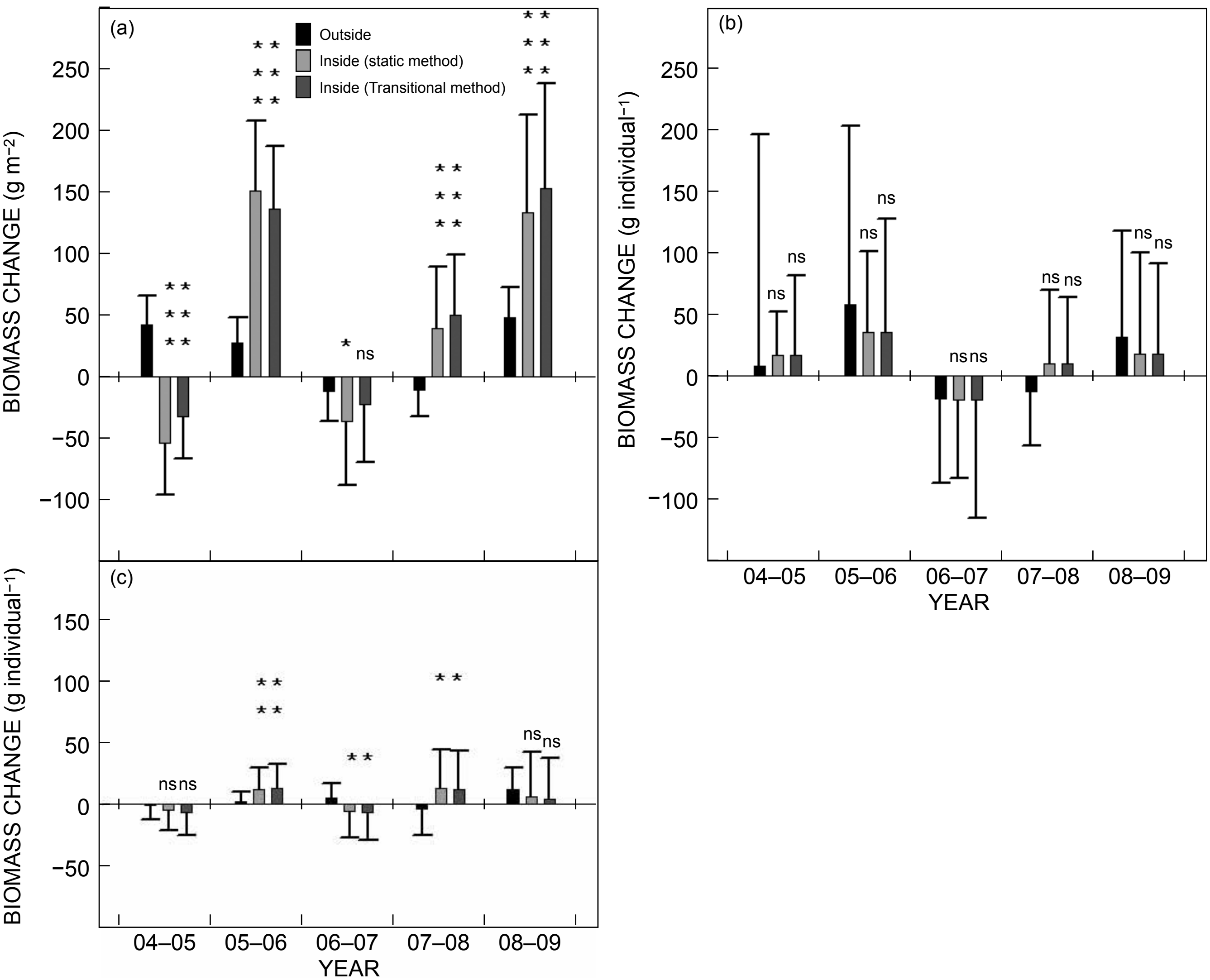

Figure 3: Mean interannual biomass changes for (a) *Artemisia herba-alba*, (b) *Artemisia mesatlantica* and (c) *Teucrium mideltense* inside (static and transitional methods) and outside the exclosure. The symbols above the bars indicate the significance of different biomass development compared to plots outside the exclosure. Error bars represent the SD. ns = $P \geq 0.05$, * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

and unbrowsed treatments was significant only with the transitional method (Table 1). The same was observed for biomass changes between subsequent years (Figure 3b).

For *T. mideltense*, the cumulative biomass change from 2004 to 2009 did not differ significantly between the browsed and unbrowsed plots (Table 1). Mean biomass hardly varied between the browsed and unbrowsed plots. Mean biomass per individual fluctuated from year to year (Figure 3c). Biomass development was significantly higher within the exclosure during only two observation periods, whereas for 2006–2007 it was significantly lower.

The results show that the volume–biomass relations of the three species behaved differently on browsed and unbrowsed plots. *Artemisia herba-alba,* which is the dominant species in the study site, was found within both treatments in all sizes from juvenile to mature. We further observed that individuals of *A. herba-alba* grew less dense with browsing. This could be because of their growth habit: individuals tended to respond to browsing pressure by developing long and sparse perpendicular twigs and shoots. With browsing exclusion, we observed that individuals developed more short and dense perpendicular shoots. Accordingly, if the same volume–biomass function would have been applied to both treatments, it would have returned biased biomass estimations.

For *A. mesatlantica*, individuals under the browsing treatment grew denser than without browsing. This result again can be explained by plant architecture with a woody base and parallel, ascending shoots. Browsing animals preferentially consume the less dense upper shoots of the plants (MF pers. obs.). Another reason for the denser plants in the browsing treatment might be the dominance of small individuals with browsing, whereas we found larger individuals in the exclosure. Tausch (1989) attributed similar results to the presence of more abundant smaller plants, which generally had denser crowns with more biomass per unit of crown volume than the fewer, larger plants.

For *T. mideltense*, the absence of differences between browsed and unbrowsed small individuals (<5 dm³) could be explained by the selective browsing of sheep. Selectivity of sheep was also documented for other North African shrubs, including *A. herba-alba* in Tunisia (Ben Salem et al. 1994). Large individuals of *T. mideltense* have a growth habit similar to *A. mesatlantica* and hence the same reasoning may apply here.

The two different approaches for biomass estimation (the transitional and static methods) yielded qualitatively similar results in *A. herba-alba* and *T. mideltense*. This congruence lends support to our estimation, and theoretically the true development must be within the boundaries defined by these two estimation approaches. The relatively greatest difference between the two methods was found for *A. mesatlantica*, which might be only because of the relatively small sample size, especially in the larger volume classes. Tausch (1989) found that the nonlinear regression method, which we chose for the present study, is the most appropriate for sagebrush species, whereas Abdelkader et al. (2008) found reasonable linear correlations for volume–biomass relationships for *A. herba-alba* in Tunisia. However, he argued that using the mean diameter of individuals resulted in a better fit than using volume estimates. We feel that further studies are necessary to gain a clearer understanding of how the two estimation approaches might affect biomass estimations in monitoring studies and which allometric parameter is most useful.

Browsing had a significant negative effect on cumulative biomass development of *A. herba-alba* over the five years. This is not surprising given the high density and palatability of this shrub (Ben Salem et al. 1994), and thus its importance to the animals' diet in comparison with the other two species. The fact that browsing had only minor effects on the two other studied species perhaps indicates that they are more resistant to browsing (Le Houérou 1980). Our findings indicate that they might even benefit indirectly from browsing through the reduction of the most competitive species in this ecosystem. According to the transitional method, *A. mesatlantica* benefited significantly from browsing over the five-year period as a whole, but not between individual years. *Teucrium mideltense*, meanwhile, did not show a cumulative difference, being affected by browsing positively in some years and negatively in others. We cannot infer too much from these inconsistent results, however, and confirmation of the potentially positive effect of browsing must await further studies.

The main merit of our study is the characterisation of volume–biomass functions for three ecologically and agronomically important dwarf shrubs in Moroccan steppe ecosystems. We have been able to show that these species change their architecture when subjected to browsing. Furthermore, we introduced two alternative approaches for the estimation of annual biomass changes based on allometric functions gained by nonlinear regression. These two approaches, i.e. the static and transitional methods, represent the two extremes of plant individual response to relaxation from herbivore pressure. The truth must lie between the values obtained by the two approaches and when both yield consistent results one can be sure about the outcome. Our study has also clearly demonstrated how plant response to browsing exclusion can differ strongly not only between species but also between years. Data from a single year is clearly not sufficient to describe plant behaviour. This was demonstrated by *A. herba-alba*, which showed a positive browsing effect for two of the five interannual transitions, but a negative cumulative effect over the study period.

Our case study was not designed to make inferences about browsing effects at the ecosystem level, as we did not replicate the treatments. However, it gives valuable insights into the processes that need taking into account in any future attempts at the ecosystem-wide quantification of browsing impact. One result meriting further investigation was the varying effect of browsing on the dominant versus two subdominant species found in our plots. Another interesting finding was how the standing biomass for all three species increased over the five years. This was strongest without browsing, but nevertheless apparent with browsing. It might be attributable to a recovery of the whole ecosystem after a long period of drought ending in the year 2000 (Born et al. 2008). This relatively quick biomass rehabilitation is a common feature of such non-equilibrium ecosystems (Finckh and Goldbach 2010). Relatively short time periods, i.e. up to 5–10 years, can apparently result in the restoration of biomass resources of the major dwarf shrub species, depending on the type of ecosystem.

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Chapter 5

Paper II

Social and ecological constraints on decision making by transhumant pastoralists: a case study from the Moroccan Atlas Mountains

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Social and Ecological Constraints on Decision Making by Transhumant Pastoralists: A Case Study from the Moroccan Atlas Mountains

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Abstract: Transhumant pastoralism is an important activity in southern Morocco. Migration pattern of transhumant pastoralists can be affected by physical factors (e.g. droughts and diseases) or socioeconomic factors (e.g. schooling options for children and migration costs). We studied the spatio-temporal rangeland usage of the three tribes Ait Mgoun, Ait Zekri, and Ait Toumert in the south-central Atlas region with a two-fold approach. First, we tracked the migration movements of one representative transhumant herd using the Advanced Research and Global Observation Satellite (ARGOS) collars, which record coordinates from satellite signals. Second, we interviewed herders to obtain information about general grazing practices of the respective tribe and to gain more direct information on motivations underlying decisions. For each tribe we observed small-, medium- and large-scale movements. We found that the most important drivers of migration decisions were seasonal fodder availability and weather conditions in combination with herd-specific risk and cost assessment, as well as personal factors. In conclusion, general migration patterns vary in time, both between and within the tribes, but according to a regulatory framework. Moreover, it appears that both the customary rules and its flexible adaptation to physical constraints are generally beneficial in terms of conservation of the arid and semiarid rangeland resources.

Key words: Ait Mgoun; Ait Zekri; Ait Toumert; ARGOS; Goat grazing; High Atlas; Jebel Saghro; Migration pattern; Rangeland; Small ruminant; Transhumance

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Introduction

Livestock grazing occupies over a quarter of the terrestrial surface worldwide (Steinfeld et al. 2010). Extensive grazing systems of arid lands are often subject to overgrazing, leading to soil degradation (Steinfeld et al. 2010). Pastoral mobility is important for the management of the sparse dryland vegetation and the conservation of these fragile ecosystems (Koocheki and Gliessman 2005). However, the long-term continuation of pastoral mobility faces several obstacles such as the extension of crop farming and national or administrative borders (IIED and SOS Sahel 2010). In Morocco, 25 to 30% of small ruminants (sheep and goats) are kept in various mobile systems, from pure nomadism to short-distance summer transhumance (Bourbouze 2006). Nomads follow a seasonal migration pattern that can vary from year to year and do not create permanent settlements (Tegegne et al. 2009). They live exclusively on livestock rearing (Werner 2004). Transhumants practice seasonal mobility with their livestock between fixed summer and winter pastures (Blench 2001). They also practice crop cultivation and have permanent settlements (Tegegne et al. 2009).

In southern Morocco, about 93% of the Draa catchment area is used as rangeland by mobile and sedentary pastoralists (Finckh and Goldbach 2010). The principal livelihood activity in this region is pastoralism and irrigation agriculture. The pastoralists have customary land-use rules regulating grazing rights between and within tribes (Saqalli et al. 2002). A very common management tool is the *Agdal*, which is a collective property used by the tribes. These have boundary limits, as well as opening and closing dates fixed by customary rules (Ilahiane 1999). Mobile pastoralism suffers from several problems, the most acute of which is the perpetual loss of rangeland surface due to the increasing sharing of communal land between different ethnic groups for cropping purposes (Werner 2004) and politically driven sedentarization (Chiche 2007). The transhumant pastoralists believe that pastoral resources have become degraded over the last 20 years due to drought (SENS 2005). Another problem is the lack of coincidence between communal boundaries and tribal territories (Finckh & Kirscht 2008; Rössler et al. 2010). This spatial incongruity is a key obstacle for sustainable rangeland management.

Despite several studies conducted in this region (Saqalli et al. 2002; Werner 2004; Kemmerling 2008; Bauman 2009; Freier et al. in press a), there is a lack of knowledge about the drivers of decision making on the how, if and when of transhumants' migration. Most relevant studies are unpublished reports, while published work only describes generalized migrations or focuses on single tribes. By contrast, we conducted a study with spatially explicit data for transhumant migrations and discussed the drivers behind individual decisions. Furthermore, we compared migration patterns between three neighbouring tribes with different ecological conditions relating to the spatial extension of summer, transition and winter pastures.

The aim of this paper was to outline the social and ecological framework for decision making by mobile pastoralists, based on a conceptual spatial estimate of rangeland and seasonal fodder availability for transhumant herders, and climatic constraints. We discussed the decisions of selected herders of the tribes Ait Mgoun, Ait Zekri and Ait Toumert against this background. We were especially interested in the degree of freedom for their individual decisions and the main reasons behind them. For this purpose, we combined semi-quantitative tracking data to follow the trajectory of selected herds within the year, with structured interviews to assess the general validity of our observations. Our results on the drivers and constraints that are influencing decision making by mobile pastoralists regarding spatio-temporal pasture selection help to improve strategies for rangeland management. Based on our results we also discussed the utility of the two chosen methodological approaches, alone or combined, to provide convincing answers to the questions addressed.

1 Methods

1.1 Study area

The study was conducted in the area between the Central High Atlas and the Jebel Saghro, in south-central Morocco (30.8–31.8° N, 5.8–6.8° W) (Figure 1). The uppermost vegetation belt of the High Atlas between 2,400 m and 3,400 m a.s.l. is dominated by thorny cushion shrubs and hemicryptophytes. These so-called Oromediterranean ecosystems represent the summer rangelands of the studied tribes. The lower mountain ranges in the High Atlas and the uppermost parts of the Jebel Saghro are dominated by Ibero-Mauretanian sagebrush steppes with dwarf shrubs, perennial grasses, and a multitude of annuals emerging in spring (Finckh and Poete 2008). Rocky outcrops of limestone and sandstone, and north-facing slopes are partly covered by juniper-sagebrush steppes. These rangelands constitute mainly transitional pastures used during autumn and spring. The southern Atlas foreland and the Jebel Saghro are covered by pre-Saharan semi-deserts dominated by the chamaephytes *Hammada scoparia* and *Convolvulus trabutianus* and are used as rangeland mostly between autumn and spring.

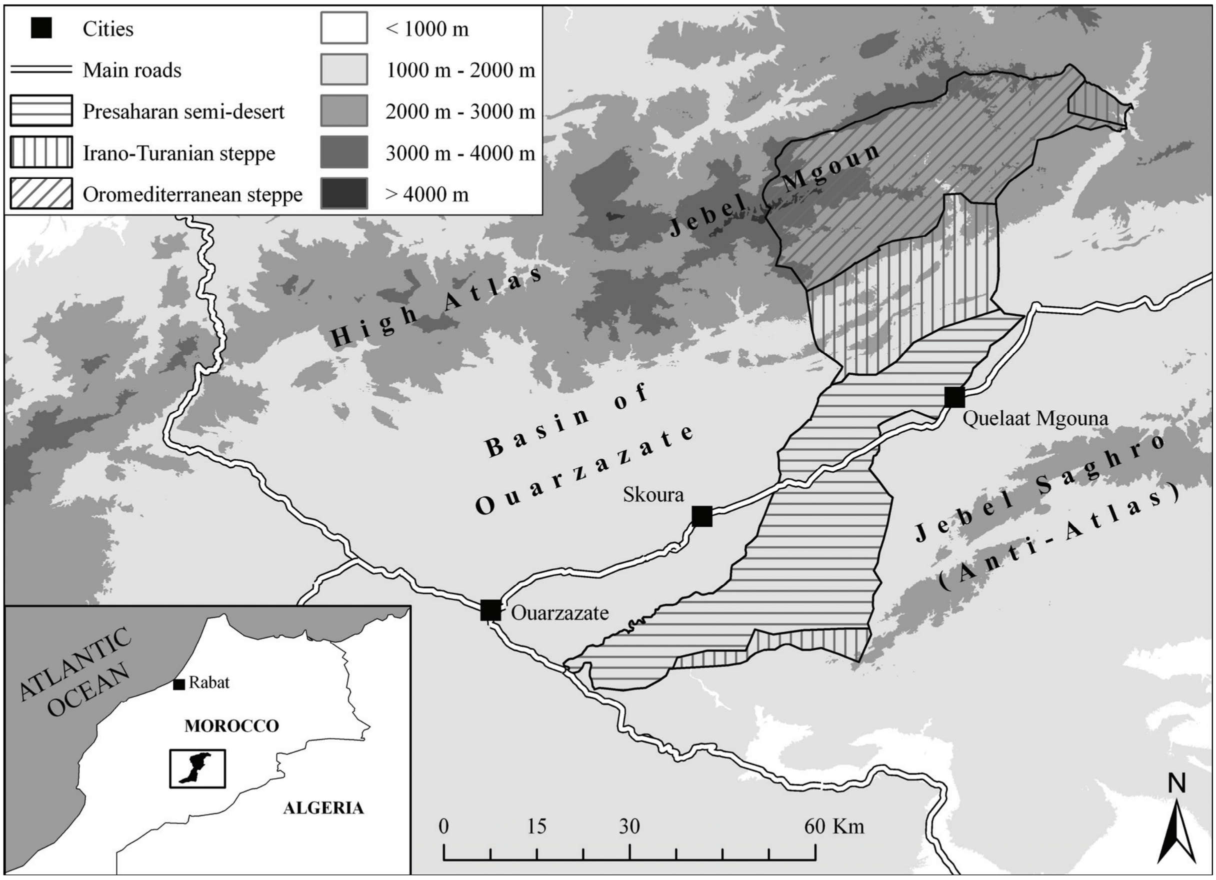


Figure 1 Location of the study area between the Central High Atlas and the Anti-Atlas in southern Morocco. The study area is divided into three major vegetation zones. A digital elevation model is displaying the topography within the region in a grey scale.

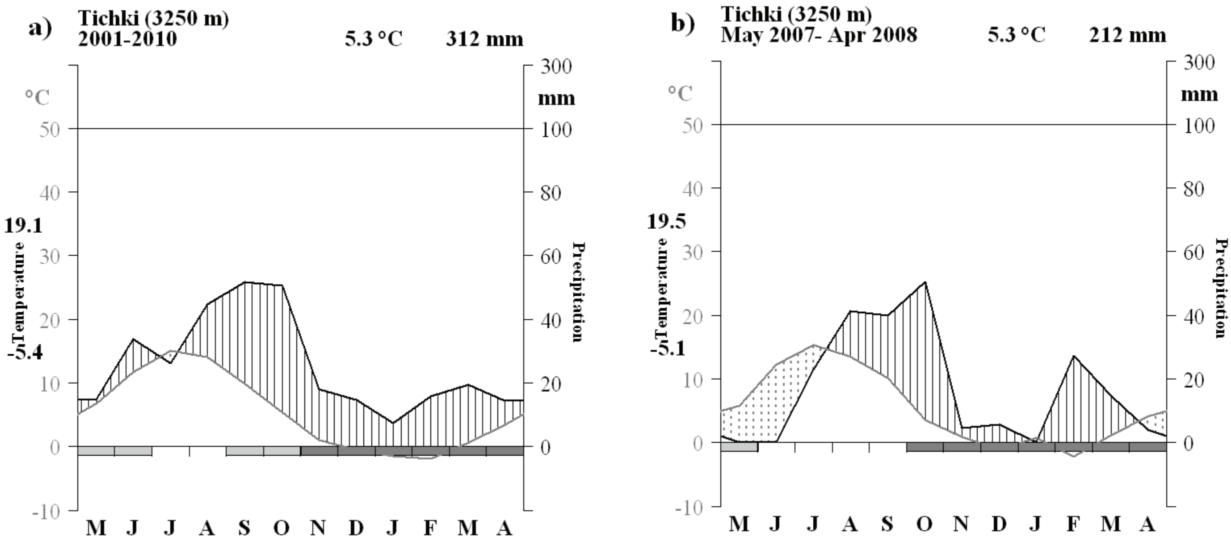
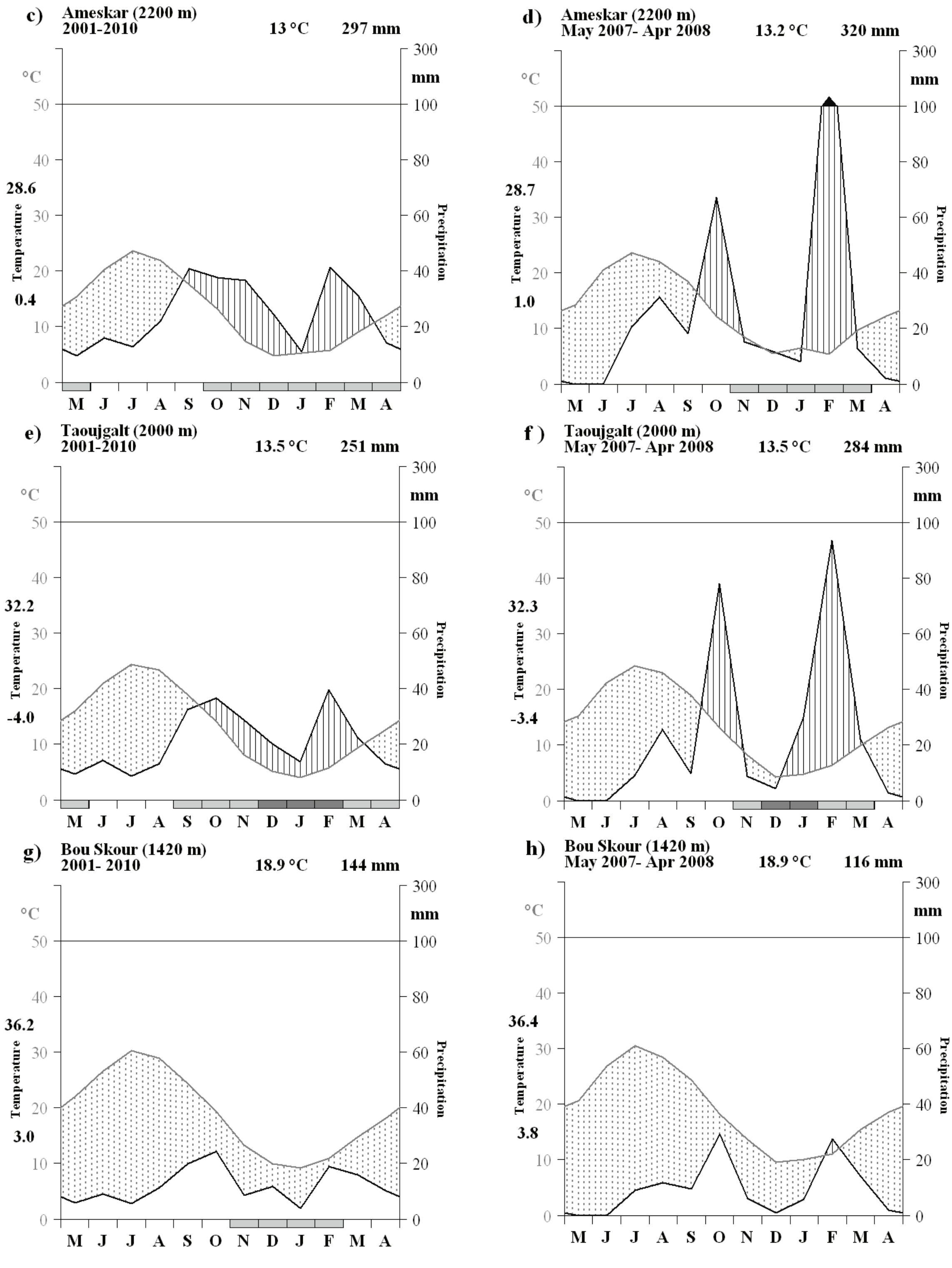


Figure 2 Walter-Lieth diagrams of four sites in the study area for a ten-year period (a, c, e, g) and from the one year studied period (b, d, f, h). (To be continued)



(Continued) **Figure 2** Walter-Lieth diagrams of four sites in the study area for a ten-year period (a, c, e, g) and from the one year studied period (b, d, f, h).

Notes: The numbers above the figures represent the mean annual temperature and the mean annual precipitation. The black curve represents precipitation in millimeters and the grey curve represents temperature in degree Celsius. Dotted areas represent an arid season, while the area with bars represents a humid season. The upper number on the left y-axis equals the mean daily maximum temperature of the warmest month, and the lower number the mean daily minimum temperature of the coldest month. The rectangles below the x-axis represent the period of sure frost (dark grey) and a period of probable frost (light grey). Note that the sequence of months in the diagrams starts with May, deviating from normal Walter-Lieth diagrams.

The region is characterized by high climatic variability in time and space (Fink et al. 2008). The bioclimates range from sub-humid in the High Atlas to arid in the Basin of Ouarzazate and the Jebel Saghro (Oldeland et al. 2008). The mean annual precipitation varies between more than 565 mm in the High Atlas and less than 135 mm in the Atlas foreland (Figure 2). The mean annual temperature varies from 5.3 °C in Tichki to more than 18 °C in Bou Skour (Schulz 2008; see Figure 2).

1.2 Interviews with herdsmen

We conducted 29 structured interviews with transhumant herders from the three tribes inhabiting the region: Ait Mgoun, Ait Zekri and Ait Toumert. The interviews were conducted between November 2008 and June 2009, either at the transhumant's camp in the easily accessible pastures or at the weekly market visited by a high number of transhumant pastoralists. The interviews were carried out in the Arabic language and when necessary in the local language, Tachelhit, with the help of an interpreter. The questions focused on the number of animals owned by the transhumant pastoralist, the trajectories of seasonal migrations, the periods spent in each pasture and the factors influencing decisions on the direction of transhumance (Appendix 1). The transhumant pastoralists in the three tribes are organized in transhumant associations. Therefore, we collected general information about the tribes by interviewing the chairmen of these associations.

For the sake of convenience, we classified the annual movements of the transhumant pastoralists of the region into four categories: semi-sedentary (less than 20 km), short-distance transhumance (20–40 km), medium-distance transhumance (40–100 km), and long-distance transhumance (more than 100 km).

1.3 Satellite tracking of herds

We selected one transhumant herd from each of the three studied tribes for animal tracking. Generally, the herds in the study area consist of small ruminants (goats and sheep) and a small number of dromedaries and equids (mules and donkeys) used for transporting tents and baggage during migration and for fetching water. The tracked herds consisted only of goats and were guided by herdsmen (Table 1). The transhumant pastoralists guide their herds in pastures surrounding a series of temporary camps within their rangelands (Table 1).

Table 1 General data on the studied tribes and herds

	Tribe		
	Ait Mgoun	Ait Zekri	Ait Toumert
Number of goats in the tracked herd	600	220	600
Village of the tracked herd	El Mrabitine (High Atlas, 2,900 m a.s.l.)	Azaghar n'Oughyoule (Jebel Saghro, 1,400 m a.s.l.)	Ait Toumert (High Atlas, 1,900 m a.s.l.)
Rangeland area (Chiche 2003)	From the ridge line of the High Atlas to the Dades Valley	From the summit of the High Atlas down to the central Jebel Saghro	Buffer zone between the territories of the Ait Zekri and the Ait Mgoun
Placement of permanent settlements (own observation)	Mostly in high and mid-altitudes (High Atlas)	From high to low altitudes (High Atlas) + Jebel Saghro	Mostly in mid-altitudes (High Atlas)

Table 2 Daily ARGOS collar records from the three herds

	Tribes		
	Ait Mgoun	Ait Zekri	Ait Toumert
Measured period	24 April 2007–23 March 2008	24 April 2007–26 April 2008	26 April 2007–21 April 2008
Missing records	176	298	305
Number of outliers	120	53	32
Available records	91	50	40

We used ARGOS (Advanced Research and Global Observation Satellite) transmitter collars (model 5035 PTT, Habit Research Ltd. (Victoria, BC, Canada)) on a single goat from each herd to follow the trajectory of the herds. The collar sends signals to the ARGOS Satellite System on the x, y, z positions (i.e. longitude, latitude, and altitude) of the goat, and these can be subsequently downloaded from a website. The satellite transmits signals during four hours per day and allows one record per day. However, days without position fixes were frequent in some periods due to satellite transmission problems (Table 2), most probably due to the rugged terrain of the study zone. In an earlier trial with the Ait Toumert herd, we used a GPS collar for the month of April 2007 on the same goat that later carried the ARGOS collar.

In a pre-study, we additionally used a GPS PLUS-1 Store On Board Collar from Vectronic Aerospace (Berlin, Germany) on three goats from three different herds. The GPS collar recorded the $x/y/z$-coordinates of the goat (i.e. latitude, longitude, and altitude) every two hours from 6:00 to 22:00. This was to assess the areal extent and the grazing radius of the transhumant herd used around a camp.

1.4 Data analysis

We visualized and checked the ARGOS data using ArcGIS 9.3 (ESRI 2010). We removed records judged to be incorrect outliers (Table 2) on the basis of a distance > 20 km to either the previous or next day's location. No such outliers occurred for the GPS collar.

The results of the pre-study showed that the grazing patterns were similar to those found around stables of sedentary herds of the region (Akasbi et al. unpublished data), with a maximum distance of 3,000 m from the stable being covered by the herds (Appendix 2). To model the rangelands available for transhumant herds, we thus used spatial buffers of 3,000 m around all villages in the study area. The areas within the buffers were considered as the main territory for sedentary herd use because mobile herders try to avoid competition with village herds. The areas outside the buffers were considered out of reach of village herds and therefore exclusively used by transhumant pastoralists.

For each herd, we created polygons representing the different pastures visited during the year. We chose the points matching a successive time sequence in the same area and then created a minimum convex polygon around them. We obtained the tribal territories from a previous study (Projet CBTHA 2008). Information on the vegetation zones in the study area was taken from Finckh and Oldeland (2008**)**. In order to understand the distribution of rangelands available for each tribe in each vegetation type, we calculated the area available per tribe in the different ecological zones by intersecting the tribal territories and the vegetation belts in the GIS.

2 Results

2.1 Rangeland distribution in the territories of the tribes

In terms of the number of transhumant pastoralists and animals, the Ait Mgoun is the biggest tribe, followed by the Ait Zekri and the Ait Toumert (Table 3). The rangelands of the Ait Mgoun and the Ait Zekri are more than twelve times larger than those of the Ait Toumert (Table 4). Rangelands accessible by the transhumant herds are larger than those accessible by the sedentary herds within each of the three tribes. This situation is more pronounced in the case of the Ait Zekri, where the transhumants' rangelands are four times larger than the ones of the sedentary herds. Regarding vegetation, most of the rangelands of the Ait Mgoun and the Ait Toumert belong to the Oromediterranean zone of high altitudes, while most of those of the Ait Zekri are in the semi-desert (Table 4).

2.2 Interview analyses regarding migration patterns

Migration patterns of the transhumant pastoralists depended firstly on the tribal territory and grazing rights of each tribe (Table 3). During the period of investigation, all the interviewed pastoralists spent the summer season in their tribe-specific *Agdals*, but this was not necessarily so in the other seasons. For the Ait Mgoun, 77% of the interviewed transhumants practice long-distance

Table 3 Transhumant herds of the three studied tribes and their rangelands (results from our interviews)

	Tribes		
	Ait Mgoun	Ait Zekri	Ait Toumert
Number of transhumants	194	84	29
Total number of sheep and goats	> 100,000	> 30,000	> 18,800
Summer rangeland	*Agdal* Ouzighimt in the Jebel Mgoun	*Agdals* Tiguitim and Marat in the Jebel Mgoun and Jebel Aklim	*Agdal* Awajgal in the Jebel Mgoun
Transition rangeland	Plains of Azaghar n'Igher and Timassinine	The plains of Timassinine and Azaghar n'Igher	Jebel Asselda
Winter rangeland	Jebel Saghro or Imlil	Jebel Saghro and Imlil	The plains of Imlil, Timassinine, Jebel Saghro

Table 4 Percentage of the area per tribe, sedentary and transhumant herds for each vegetation type in the study area

	Tribes								
	Ait Mgoun			Ait Zekri			Ait Toumert		
Vegetation types	S	T	All	S	T	All	S	T	All
Oromediterranean zone (%)	24.9	63.4	49.0	19.5	4.5	7.3	65.4	99.1	81.7
Irano-Turanian steppe with *Artemisia* (%)	46.9	21.8	31.3	19.3	18.1	18.27	34.5	0.9	18.3
Semi-desert with *Hammada scoparia* (%)	28.2	14.7	19.8	61.2	77.4	74.3	0	0	0.0
Total (ha)	50,845	85,347	136,192	22,905	98,893	121,798	4,941	4,654	9,595

S= Sedentary; T= Transhumant.

migrations from the High Atlas to the Jebel Saghro, especially during rainy years with good development of annual vegetation, while 23% practice a medium-distance trajectory from the high mountains to the plain of Imlil in the Atlas foreland. They spend the transition period in the sagebrush steppes of Timassine and eastern Azaghar n'Igher. Short-distance transhumance trajectories are generally preferred in dry years. From the interviewed Ait Zekri, 63% travel the long distance between the Jebel Saghro and the high mountains, 27% practice semi-sedentary movements within the Jebel Saghro, while the other 10% practice short- to medium-distance journeys between the high mountains and the mid-altitude plain of Azaghar n'Igher. Within the Ait Zekri, we found two groups. In wet years with good fodder availability, the transhumant pastoralists originating from Jebel Saghro sometimes prefer semi-sedentary movements in Jebel Saghro, which offers extended rangelands with high quality fodder plants. Here, the animals are reported to be healthy and grow better. They migrate to the High Atlas in summer mostly in dry years when the available forage in Jebel Saghro is not sufficient. The second group of transhumants originating from the High Atlas prefer short- to medium-distance transhumance in dry years. Within the Ait Toumert, 12% practice long-distance transhumance between the high mountains (*Agdal* Awajgal) in summer and the Jebel Saghro, but only in a cold and rainy winter. Meanwhile, 88% practice only a short- to medium-distance migration between the high mountains and the plains of Imlil or Timassinine. They spend the transition period in the Jebel Asselda.

2.3 Annual migration pattern of the tracked herds

The ARGOS data showed that the Ait Mgoun transhumant migrated with his herd between the

Atlas foreland (plain of Imlil) and the high mountain pastures in the upper Mgoun Valley (Ouzighimt) (Figure 3). He practiced a medium-distance migration during the study period following the same pattern as many interviewed transhumants. He spent the spring of 2007 in the plain of Imlil. In May he travelled through the Mgoun Canyon (Gorges du Mgoun) to the high mountain pastures of the upper Mgoun Valley for the summer season. He stayed in a high altitude *Agdal* on the southern slopes of the Jebel Waougoulzat until mid-August, and then

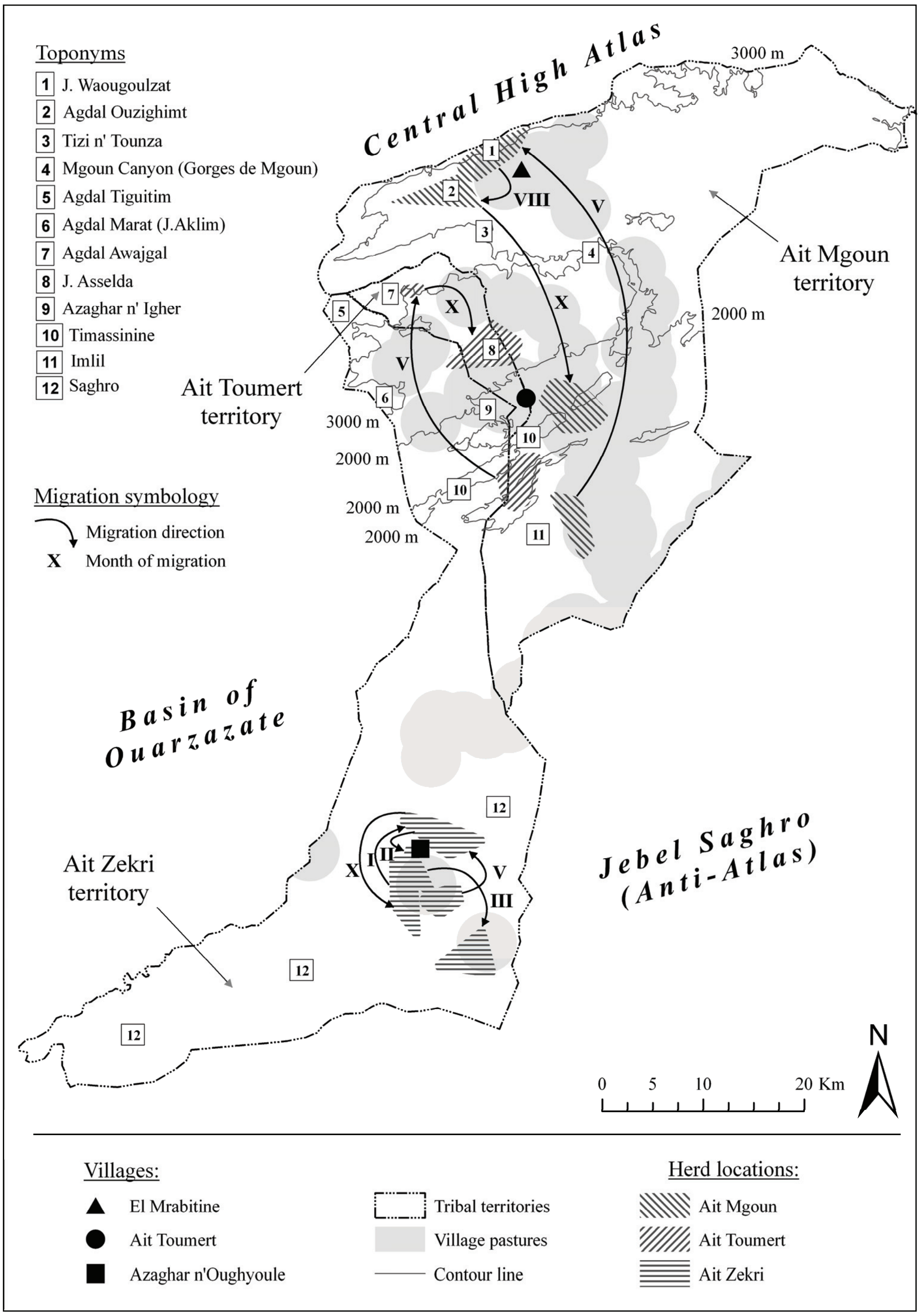


Figure 3 Map of the migration movements of the three tracked herds in the tribal territories. The arrows show the direction of migration of the herds and the Roman numbers shows the month of migration.

descended to lower altitudes close to the valley bottom west of El Mrabitine, where he stayed until October. In mid-October, he crossed the high mountain passes of Tizi n' Tounza and descended to mid-altitude rangelands of Timassinine in the Atlas foreland, where he spent the winter and spring of 2008. In conclusion, this transhumant spent the spring of 2007 and 2008 in two different ecological zones: Imlil in the pre-Saharan semi-deserts and Timassinine in the Irano-Turanian sagebrush steppes.

The Ait Zekri transhumant stayed in the semi-desert pastures of Jebel Saghro during the whole study period, following a semi-sedentary movement. This contrasted with the normal pattern of migrating in summer towards the High Atlas (Figure 3). During the year, he shifted his camp five times searching for good pastures. The movements of his herd were limited to a relatively small area of less than 20 km from his village of origin, and twice in the observation period he returned for a while to his permanent house (June – September 2007 and February 2008).

The Ait Toumert transhumant followed a medium-distance trajectory, like most of the Ait Toumert. In spring 2007, he guided his herd in mid-altitude sagebrush steppes in the territory of the Ait Mgoun and the Ait Zekri south of the village of Ait Toumert, which is where he has a house. In May 2007, he moved from there to the high mountain *Agdal* Awajgal, on the southern slope of the Jebel Mgoun (4,060 m a.s.l.), where he spent the summer season. In October, he descended to the Jebel Asselda in the lower Oromediterranean zone, directly north-west of Ait Toumert, for the winter of 2007/2008 (Figure 3). Again, as in the case of the Ait Mgoun herder, he spent the winter of 2008 in a different, higher-situated, pasture than in the winter of 2007.

3 Discussion

3.1 Ecological and social factors shaping the migration patterns

We aimed to identify the relevant ecological and social factors that influence decision making of herders in the Atlas Mountains of southern Morocco. We found five major factors, which are discussed in the following paragraphs, bringing together the results of our two partial studies, the interviews, and the satellite tracking of the herds.

3.1.1 Fodder availability

The transhumants choose their pastures according to fodder availability and quality in order to meet the needs of their animals. This is supported by the observed trajectories of the transhumants as well as by the interviews. The Oromediterranean high mountain pastures are dominated by perennial plants, being reliably productive during the summer months and offering high quality fodder for the animals. When the high mountain *Agdals* open in mid-May, the pastures have rested for the whole winter and a good part of the spring, giving the vegetation enough time to recover from the last grazing season. Moreover, summer migration to the high mountain pastures allows the mid- and low-altitude steppes to recover after the spring grazing season, with their plant-life left to resprout relatively undisturbed after the first autumn rains. Such transhumance patterns, driven by fodder availability, are found throughout the world. In Tanzania, Maasai herders are well aware which landscapes are most productive in a particular season (Oba and Kaitira 2006). In the floodplain in Cameroun, the pastoralists practice a transhumance following the rain and looking for fresh forage for their animals, a strategy called 'watching the clouds' (Moritz et al. 2010). Similarly, In Iran the Komachi transhumants migrate seasonally from lowland winter pastures on the coastal plains of the south of the country to highland summer pastures close to the city of Kerman, following the availability of needed resources (Salzman 2002). Hence, for nearly all transhumants, fodder availability is the key factor for making decisions on where to take their herds. These patterns are usually adapted to seasonal weather conditions coupled with a resting system for the vegetation.

3.1.2 Harsh climate

Harsh climates can influence transhumance behaviour by limiting usability or even accessibility of certain parts of the study region. Seasonal vertical migration is a good strategy to avoid the severe cold winters in the high mountains and the hot summers at lower altitudes, which in both cases can otherwise impact negatively on the transhumants and their animals alike. At high altitudes, winter mean temperatures descend below 0 °C (Figure 2a-b) and there is the risk of getting trapped with the herds by longer-lasting snow cover. The mean temperature at lower-lying pastures is about 10 °C in the winter. By contrast, in summer the climatic conditions are comfortable in the high mountains with mean temperatures between 10 °C and 18 °C, compared to mean temperatures reaching more than 30 °C in the basin of Ouarzazate and in the Jebel Saghro (Figure 2a-b, g-h). In Morocco, this transhumance, either in the vertical or horizontal direction, was also observed in other regions such as the Middle Atlas, eastern Moroccan High Plateaus and southern Moroccan desert (Bourbouze 2000). In mountainous countries, this seasonal vertical migration is a well-known strategy. Until the 1930s it was practiced in Kyrgyzstan, where the nomads used to spend the summer in the mountainous pastures and descended to lower altitudes in winter because of low temperatures and snow (Borchardt et al. 2011). The same patterns have been observed in Tibet (Dupuis 1970), Abruzzo in central Italy (Morbidini 2002), and South Africa (Samuels et al. 2008). It seems that harsh climates, with their unbearable cold or hot weather conditions for the transhumants and their herds, are an important factor driving decisions on their vertical seasonal migration.

3.1.3 Grazing rights

Tribal boundaries limit the grazing rights of each tribe and thus act as a social constraint on the spatial expansion of the migration patterns. The transhumants generally prefer to graze within their tribal territory, and according to their grazing rights. This avoids conflicts with other tribes, or helps gain support in case of conflicts. However, sometimes tribes have seasonal grazing rights in the tribal territory of other tribes. For example, the Ait Mgoun are allowed to graze in the Jebel Saghro even though it belongs to the Ait Zekri territory, following an agreement between both tribes in 1950 (Chiche 2003). For this reason, many Ait Mgoun herders migrate to this pasture in winter. The Ait Toumert transhumants are also allowed to graze their animals during winter in the territory of the other two tribes because of their historically good relations and low numbers. This is the reason why the tracked herd of Ait Toumert used the adjacent territory of both tribes (Figure 3). However, the Ait Toumert transhumants generally avoid the Jebel Saghro and visit it only in cold and rainy winters to avoid resource competition with the other tribes. We find similar rules in other regions in the High Atlas. The tribes Rheraya and Ourika share the grazing rights in two defined parts of the *Agdal* Oukaimeden; the crossing of other territories by migrating herds is also tolerated (Mahdi 1999). However, sometimes inter-tribal conflicts regarding land-use rights and pasture territories occur and clashes have been reported to be violent (Chiche 2003).

3.1.4 Rangeland distribution

The distribution of tribal rangelands – their locations, sizes and major vegetation types – is an important factor in decision making on transhumant migration (Table 4). While the vast high mountain pastures of the Ait Mgoun allow for a large number of transhumant herders and animals, their mid-altitude rangelands are relatively small. Hence there is always a considerable pressure for the individual herder to engage in the long-distance migration towards the Jebel Saghro. By contrast, The Ait Zekri have only small Oromediterranean pastures in the High Atlas, but extended pastures in the lower Atlas ranges, the Basin of Ouarzazate and the Jebel Saghro. In wet years, low-intensity grazing in the pre-Saharan semi-desert rangelands is perceived by some of them as a better option compared to a costly and sometimes risky migration towards crowded and overgrazed high mountain pastures (Freier et al. in press b). In comparison to the two larger tribes, the Ait Toumert have a compact territory, with areas mainly in the lower Oromediterranean zone and upper sagebrush steppes close to their central settlement. When weather conditions become harsh, they can relatively easily descend to the shelter of their settlements or migrate (in the case of long-lasting frost periods) towards the lowlands, without the need to cross high passes or cover long distances. The shape of their territory, in terms of topography and ecological zoning, enables them to pursue a migration pattern which would be risky for most herders of the two larger tribes. As demonstrated by the Ait Toumert herder (with

ARGOS observation), the compact Ait Toumert territory allows their transhumants to pass the winter in relatively high pastures. In the case of bad weather, they only have a short distance to the village Ait Toumert to look for shelter or to buy additional fodder. The proximity of the pastures to their main tribal centre is most important for reducing the immediate risk of calamities, but is not a long-time option for cold winters. This is shown again by the fact that the Ait Toumert herder spent the hard winter of 2006/2007 at considerably lower pastures than the milder winter of 2007/2008.

3.1.5 Individual factors and social networks

Migration patterns of herders are also influenced by social factors and networks. Summer migration allows the Ait Mgoun herders to visit their families and to reconnect with their tribal fraction. The Ait Mgoun transhumant tracked by the ARGOS satellite preferred a mid-distance rather than long-distance transhumance in the observation period. He stayed half-way between the mountain villages and the main tribal settlement and souk at Quelaat Mgouna, remaining well connected to relatives and avoiding the risks and costs of long-distance travel between his village and the Jebel Saghro (Freier et al. in press b). Many Ait Mgoun transhumants tend to spend the winter in the plain of Imlil, close to the main market town Quelaat Mgouna, while the Ait Toumert descend in autumn towards their villages and their weekly market where they can buy or sell animals. In spring, tribal members warned the Ait Zekri transhumant in the ARGOS study about cases of the blue tongue disease in the Atlas villages of the tribe. Therefore, the transhumant cancelled the long migration towards the Atlas high mountain pastures, opting for short migrations within the Jebel Saghro and around his home village. In this way, he avoided the risk of his animals becoming diseased and the costs of the long journey towards the High Atlas. In African pastoral systems, reciprocal livestock exchange either through friendships, loans or gifts is a typical strategy against the risk of losing animals as a result of threats such as drought and diseases, at the same time contributing to the rebuilding of herds (Moritz et al. 2011). The Ait Zekri transhumant returned to his house twice, during the hottest and coldest periods of the year, to benefit from some weeks of relative comfort and convenience. Over the course of the year he guided his herd close enough to the "road" to enable him or his son to visit the weekly souk at Skoura. This also meant he could go to his village every week for Friday prayers (and the corresponding exchange of news from family and tribal fraction). The same strategy was followed by the Ait Toumert herder. From autumn to spring he would always graze close to his village, so that he was able to visit the weekly souk at Ait Toumert for provisioning, news exchange and a visit to his house. Such behaviour shows how herders rely strongly on their family and tribal networks.

3.2 Patterns of transhumance in comparison with other regions

In this study, we classified transhumant migrations into four categories: long-, medium-, and short-distance, and semi-sedentary. However, there is no unified terminology for types of transhumance. Pastoral migrations have been classified according to distances covered, periodicity, duration of departure, location, and type of livestock, as well as by combinations of these aspects (Clarke 1959). Moreover, the differentiation between long- and short-distance transhumance varies according to the macro-regional context. In North Cameroun, Kossoumna Liba'a (2008) considered cattle grazing up to 5 km away from villages as short-distance transhumance while she classified long-distance as being between 20 and 100 km. In Romania, Huband et al. (2010) used the term long-distance transhumance for sheep that covered distances of 200–300 km. However, even longer-distance migrations of more than 1,000 km are documented. In this case, the herders cross province or even country borders, especially during severe droughts (Werner 2004).

Some authors do not classify transhumance by distance only. In the Maghrebian context, Bourbouze (2000) defined three major types of pastoralism based on their mobility: semi-nomadism, called also long transhumance (migration of the family with the herd over distances of more than 100 km and using tents); short transhumance, or summer transhumance, when movements are made towards mountainous pastures in summer; and sedentary, when the herd moves, often long distances, but returns to the village at night. In Northeast Benin, Djenontin et al. (2009) distinguished two types of transhumance: long transhumance (occurring outside of the pastoral territory); and short transhumance (within the pastoral territory but avoiding cultivated areas). It seems that there is no general classification of transhumance distance, most probably because distances are always relative to the extent of the respective study area. The classification of transhumance distances in our own study comes closest to that of Bourbouze (2000).

3.3 Comparison of the methods used in the study: ARGOS and the interviews

Although we could follow the approximate trajectories of the tracked herds, the ARGOS positioning was imprecise and not sufficiently effective (Table 2). From all possible data points, 52% were missing for the Ait Mgoun and more than 80% for the Ait Zekri and the Ait Toumert. Additionally, half of the remaining data were outliers with strong positioning errors. This is probably due to problems with the signal transmission in the rugged mountainous parts of the study region, and the tendency of the goats to look for shelter (e.g. under rocks) during midday or under harsh weather conditions. For these reasons, the ARGOS collar system appears to be inappropriate in such mountainous regions, and we recommend the use of GPS collars instead. They have been shown to perform well regardless of weather and daylight (Lindzey et al. 2001). A study on red deer demonstrated that GPS performance was characterized by consistently high position acquisition rates despite rugged mountainous relief, while the proportion of 3D records was relatively low compared to other studies in smoother terrain (Zweifel-Schielly & Suter 2007). From our experience both in the current study and an unpublished study on sedentary herds in the same region (Akasbi et al. unpublished data), GPS collars give much more reliable data than ARGOS collars (in terms of spatial precision and temporal continuity). Ren et al. (2009) used both types of collar to study the home range of Yunnan snub-nosed monkeys, but the ARGOS ones in their study failed. By contrast, ARGOS collars were successful in tracking wolves in the Rocky Mountains in south-west Alberta, Canada (Muhly et al. 2010). We strongly recommend the use of GPS collars, or ARGOS collars only when their performance can be tested for a short period before starting the study.

Regarding our questionnaire, one challenge encountered was the lack of accuracy of interviewees in describing the exact date of transhumance (giving only the season or month), and the trajectory of their migrations. Furthermore, rangelands were mentioned by local names, sometimes covering broad regions, and as such could not be precisely located on the map. The same problem was raised by Kemmerling (2008) who studied the local strategies of the Ait Toumert in the same region.

Both approaches (ARGOS collars and interviews) had specific strengths and weaknesses in our study, and complemented one another. Other studies support the benefits of combining local knowledge and collar data. For example, Brook and McLachlan (2009) combined conventional radio-collar data from elk with local farmer knowledge of elk and cattle farm management practices. By doing so, they were able to characterize elk habitat use and interactions with cattle, thereby identifying a proxy measure of potential risk of bovine tuberculosis transmission. Adriansen (2008) combined an interview-based approach with GPS collar data to understand the pastoral mobility of the Senegalese Fulani. From these examples, and our own work, we see how local knowledge can greatly complement animal trajectory information.

4 Conclusions

The transhumant migration decisions of the three studied tribes are dependent on both ecological and socioeconomic conditions. The key ecological factor that drives decision making of transhumant pastoralists is fodder availability. Furthermore, harsh climate in the mountains limits access to mountain pastures during autumn and winter months while during summer the arid lowlands become too hot for the herders and their animals. Individual decisions allow for flexible adaptation within the framework of the tribal and ecological settings, taking into account risk control, social networks (proximity to central tribal settlement and larger family), the arrangement of tribal territories and access to local markets. The findings based on our ARGOS trajectories were in agreement with the general migration framework deduced from the interviews with the transhumants. Both methods, interviews and ARGOS trajectories, had certain weaknesses, in particular with regard to spatial precision. However, we found that in our case study, both methods were complementing each other. This comprehensive study of migration patterns of transhumant pastoralists and the factors that influence their decisions may provide valuable information to rangeland managers of semi-arid rangelands.

Acknowledgements

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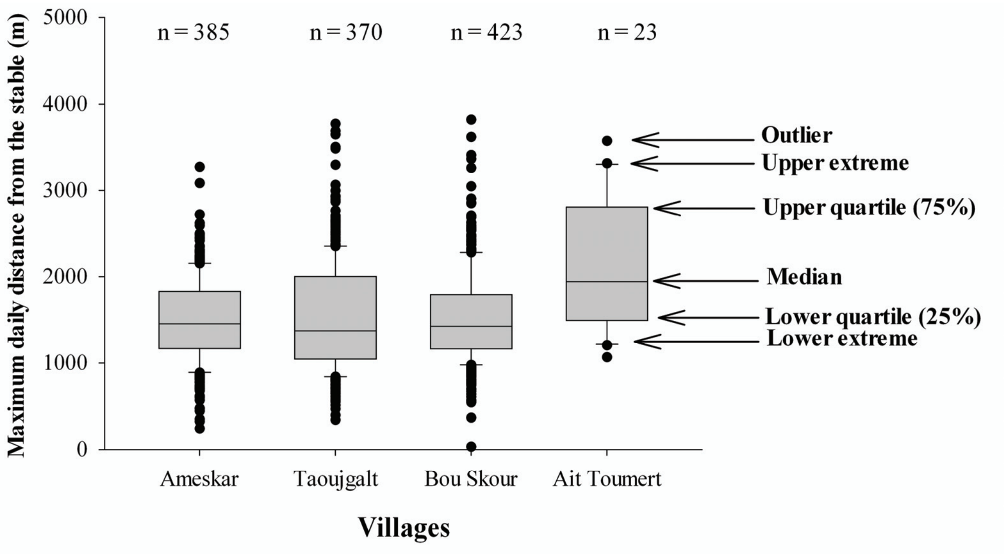
Appendix 1 Model of interviews conducted with the transhumant herders

N° Interview
1) Date
2) Name of the herder
3) Name of the village
4) Tribe of the herder
5) Number of sheep
6) Number of goats
7) Number of dromedaries*
8) Number of equines*
9) Number of sold animals*
10) Age of sold animals*
11) Sheep price*
12) Goat price*
13) Dromedary price*
14) Do you sell wool? For how much? *
15) Who is responsible for herding?
16) Where do you sell the animals (which markets)
17) Period of selling the animals*
18) Name of summer rangeland used, period spent there
19) Winter rangeland, period spent there
20) Transition rangeland, period spent there
21) Is this trajectory of transhumance the same every year?
22) Under which conditions you change the usual direction of transhumance?
23) Which are the most important factors for your decision making about migration routes?

*Data not used because they were not complete or imprecise.



Appendix 2 Boxplots of maximum daily distance from the stable for four goat herds in the study area

Notes: Ameskar, Taoujgalt and Bou Skour refer to sedentary herds. Ait Toumert is the transhumant herd under study. The box represent the lower and the upper quartile range (25% -75% of the data range), the thick line in the middle of the box represents the median. The whiskers display the total range of the data without outliers. Outliers are shown as black dots representing very large values i.e. values beyond 95% of the data range. The "n" above the boxplots represent the total number of days the herds were studied. In 98% of the days, the herds did not exceed a distance of 3000 m from the stable.

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Chapter 6

Paper III

Analysis of GPS trajectories to assess goat grazing pattern and intensity in southern Morocco

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Analysis of GPS trajectories to assess goat grazing pattern and intensity in southern Morocco

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Paper submitted to *The Rangeland Journal*

Abstract

The assessment of grazing intensity is important for choosing adequate management decisions on rangelands. Using GPS collars, we studied tended goat herds from three villages in southern Morocco. We aimed at a characterization of their spatio-temporal movement pattern, i.e. the seasonal variation in grazing intensities, and daily trajectories of the herds. Further, we assessed the effect of recording interval on recorded daily walking distances and the relationship between grazing intensities and distance. Grazing intensities (*GI*) were calculated within 4 ha grid cells for areas around home stables. We found highest *GIs* in the first 250 m around the stable. However, some directions were totally avoided due to either village boundaries or difficult topography. Depending on the climate type, daily and maximum walking distances were significantly different between seasons and were between 3,480 m and 4,460 m. In more arid ecosystems we found longest mean daily walking distance to be in spring whereas in more humid ecosystems it was in summer. This variation in grazing pattern is mainly driven by varying fodder availability, climatic conditions and the length of day. The distances were longer with higher fodder availability, while cold temperatures and short days in winter limited the distances walked. The relationship between GPS recording interval and recorded trajectory length was described well by an exponential function, which in turn allows extrapolation from data with longer intervals to the actual distances travelled. Using non-linear regressions, the decay of grazing intensity with increasing distance was described better with power functions. The exponents ranged from –1.69 to –2.18, demonstrating that goat grazing was clumped around the stables. Our description of the grazing patterns of goats in North Africa provides invaluable data for management decisions and for parameterization of grazing models.

Key Words: distance decay, grazing concentration, GPS collar, grazing intensity, non-linear regression, recording interval.

1. Introduction

Dry rangelands cover large areas worldwide and constitute a source of subsistence for millions of people (World Resources Institute 2005). However, about 15% of these dry rangelands are affected by degradation, mostly through overgrazing (Steinfeld et al. 2006), which leads to a decrease in biodiversity and productive capacity. In Morocco, 82% of the drylands are used as rangelands and contribute to the subsistence of thousands of people (Mahyou et al. 2010). In recent years, however, rangelands have suffered from severe degradation and reduced production (Fikri Benbrahim et al. 2004). For instance, in the Central and Oriental High Atlas 45% of the rangelands show symptoms of desertification (Mahyou et al. 2010). Overgrazing has been identified as one of the main drivers of degradation. To deal with this situation, an evaluation of grazing intensities, the key management variable (Dumont et al. 2007) of these arid rangelands, should be a priority in management strategies.

Grazing intensity, as defined by Holechek et al. (1998), are the cumulative effects of grazing animals on rangelands during a particular time period. Its assessment is very complex in open collective rangelands of southern Morocco, due to the difficulty of quantifying the number of grazing animals and their spatio-temporal movement patterns. The rangelands of southern Morocco are used by sedentary and transhumant pastoralists (Akasbi et al. 2012 a). Customary laws regulate the utilization of rangelands by the herders, both between villages and within the same village (Bourbouze and Gibon 2000; Saqalli et al. 2002). However, the legal status of collective rangelands is often not clearly defined. Differences between administrative and tribal territories impede management decisions and blocks revenues resulting from collective lands. Ambiguity in the legal status of collective lands often favours long-term strategies for individual land claims that might block sustainable management decisions (Finckh and Kirscht 2008). Furthermore, the abandonment of traditional pastoral practices accelerates the deterioration of rangeland conditions (Werner 2004).

Given the urgency of the conservation and sustainable utilization of these rangelands, there is a need for researchers to contribute to the development and implementation of management strategies by evaluating current land use practices and intensities. For this purpose, Global Positioning System (GPS) collar techniques are effective tools for tracking livestock over time (Biggs et al. 2001). Several authors have used them for the determination of herd itineraries and grazing areas (Rutter et al. 1997; Schlecht et al. 2006) or for the quantification of grazing intensities and the study of animals' behavior (Kawamura et al. 2005; Tomkins & O'Reagain 2007; Putfarken et al. 2008). Most of these studies have been conducted in Europe and the USA, but we are not aware of any study in North Africa. Since the year 2000, the accuracy and reliability of GPS collar data has improved (Tomkiewicz et al. 2010) and the problem of positional errors has been reduced (Frair et al. 2004). However, the limited battery power of GPS collars creates a trade-off between long recording periods without battery change and high temporal recording resolution. As temporal resolution influences the perceived distance travelled by the animals (Pépin et al. 2004; Johnson and Ganskopp 2008) adequate statistical approaches are needed if one wants to combine extended recording periods with accurate data.

Despite some recent studies on rangeland management in southern Morocco (Finckh and Goldbach 2010; Freier et al. 2011; Akasbi et al. 2012 b), there is still a lack of empirical baseline data on spatio-temporal grazing patterns in this region. We do not have any information concerning the grazing radius of tended goats, the mean length of their daily itineraries and the physical and social factors delimiting the spatial extension of the grazing areas. We have neither any reliable estimations of grazing intensity for southern Morocco nor the methodological framework to assess how the seasonal overlap of sedentary and mobile herds influences grazing pressure. A better understanding of spatio-temporal grazing patterns would allow the development of spatially explicit models of rangeland productivity and improve decision support for rangeland management.

Our present study mainly aims to provide a detailed description of spatial and temporal grazing patterns of goat herds. We tracked three tended sedentary goat herds in southern Morocco using GPS collars in order to understand their spatio-temporal grazing pattern. With this study, we address the following questions: (i) How do the herds use the space around their stables during the course of the year? (ii) How high are the grazing intensities in the three sites and could they be described according to a general model? (iii) Do the daily trajectories of the goats follow certain patterns? In order to derive data from GPS records of relatively low temporal resolution, we additionally investigated the question: (iv) What is the effect of recording interval on perceived daily travelling distance? We developed a statistical approach to deal with this latter issue.

2. Materials and methods

2.1. Study area

The study was conducted at three villages in the province of Ouarzazate in southern Morocco along an altitudinal gradient (Figure 1). The village Ameskar is situated at about 2200 m a.s.l. in a narrow valley on the southern slopes of the main range of the Central High Atlas. The second village, Taoujgalt, is located at about 2000 m a.s.l. at the periphery of a large intra-montane basin in the southern ranges of the Central High Atlas. The third site is the small settlement of Azorz close to the mines of Bou Skour, situated at 1420 m a.s.l. in the rocky hills of the northern Jebel Saghro which is the eastern range of the Anti-Atlas. In the following, we refer to this site as Bou Skour.

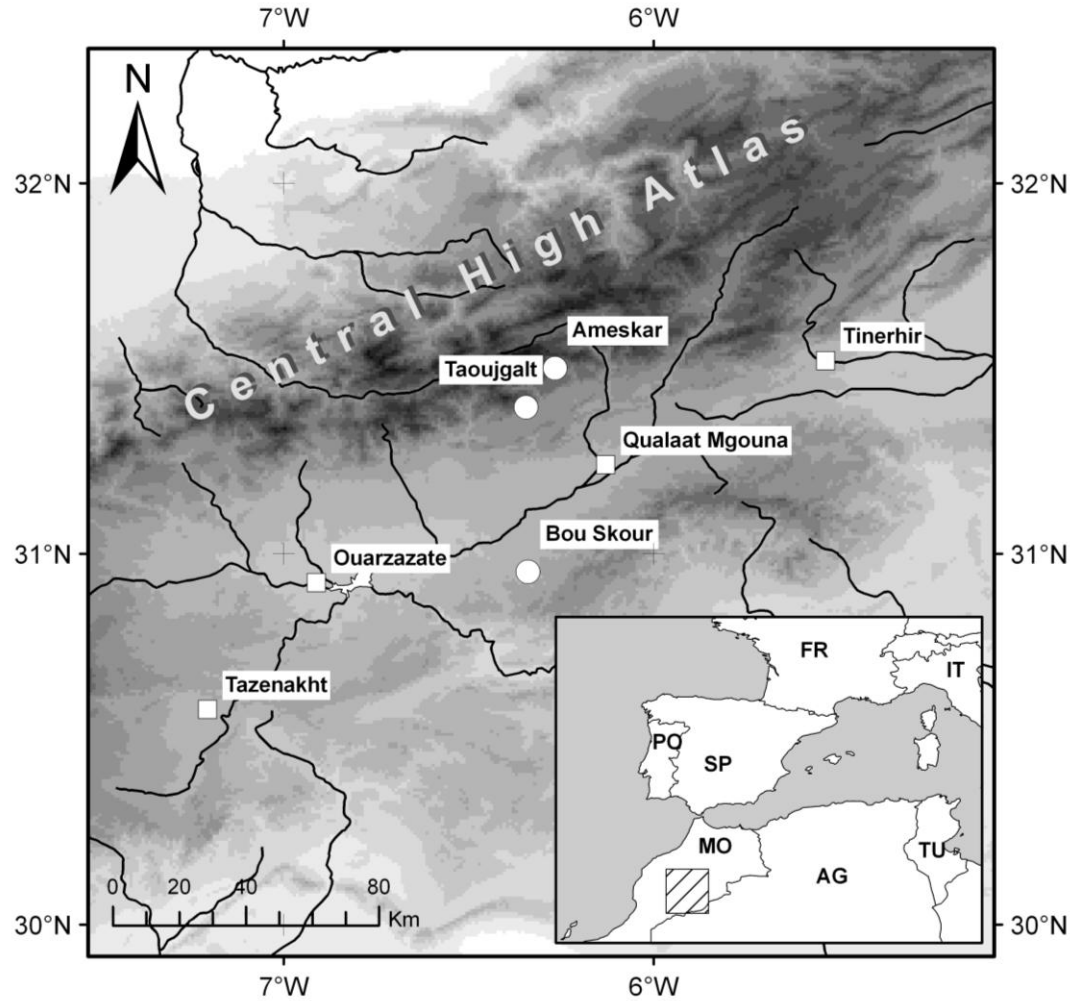

Figure 1. Location of the study area in southern Morocco.

The village Ameskar lies at the bottom of a deep west–east stretching valley. In the lower mountain belt of Ameskar, the vegetation is an open juniper–sagebrush steppe dominated by three *Juniperus* species, three *Artemisia* species, several *Stipa* species, as well as *Teucrium* species (Schulz et al. 2010). The soils are skeletic Calcisols and calcaric Leptosols on the slopes, whereas Fluvisols occur on the floor of the valley (Miller 2002).

The village Taoujgalt lies in the foothills of the Atlas chain on a small plateau. The vegetation in the plains corresponds to a sagebrush steppe dominated by dwarf shrubs such as *Artemisia herba-alba* Asso, *Artemisia mesatlantica* Maire, and *Teucrium mideltense* (Batt.) Humbert. On the slopes north-west of the village, the vegetation is similar to that of Ameskar. In terms of soil types, the plain is characterized by calcaric Leptosols and lepti-calcaric Regosols whereas leptic Calcisols occur on the slopes (Miller 2002).

The site of Bou Skour lies on a slightly undulating plain that is dissected by several dry riverbeds. The vegetation corresponds to a semi-desert dominated by the Saharan dwarf shrubs *Hammada scoparia* (Pomel) Iljin and *Convolvulus trabutianus* Schweinf. & Muschl. accompanied by other dwarf shrubs. In spring, a large number of therophytic grasses and herbs produce a short boost of fresh biomass (Nedderhof 2009). Predominant soil types are calcaric Regosols as well as lithic and chromic Leptosols (Weber 2004), interspersed with basaltic outcrops (Schulz et al. 2010).

The three sites represent a climatic gradient from semi-arid and relatively cold conditions in Ameskar to per-arid and much warmer conditions in Bou Skour (Table 1, Electronic Appendix 1). The areas around the three settlements are used by transhumant and sedentary goat and sheep herds (Akasbi et al. 2012 a). The herds under the current analysis are sedentary and consist exclusively of goats. They graze from morning to evening in the surroundings of the settlements, always guided and kept together by herdsmen. Overnight, they are kept in a stable within the respective settlement.

2.2. Data collection

In each village, we selected a strong and healthy goat from one of the tended herds (Table 1) for GPS tracking during the whole study period. The goat was assumed to indicate the daily itinerary of its tended herd. For the village Ameskar, the selected herd is assumed to be representative for the whole village because it was logistically not possible to monitor all herds. We used a GPS PLUS-1 Store On Board Collar from Vectronic Aerospace. The GPS collar recorded the *x/y*-coordinates of the goat (i.e. longitude and latitude) from 6 to 22 hours. Two different time resolutions (15 min; 2 h) were used in order to (i) analyze the effects of temporal resolution and (ii) maximize battery life.

In Ameskar, the data covered the periods from April 2007 to January 2008 and from November 2008 to January 2009. The recording interval was set to 2 h for the first period and to 15 min for the second period. In Taoujgalt, data recording covered the periods from April to October in both 2007 and 2008. Here, a recording interval of 2 h was used. Data recording was interrupted from October 2007 to April 2008 by a short-circuit in the GPS device. In Bou Skour, data recording covered two periods: from March to October 2007 and from November 2008 to June 2009. We used a two-hour recording interval during the first period and 15 min in the second.

Table 1. Overview of climate and land use data for the three study sites. If no source is given, the information is based on the authors' observations.

	Ameskar	Taoujgalt	Bou Skour
a) Location	31° 30' N, 6°14' W	31° 23' N, 6° 19' W	30° 57' N, 6°20'W
b) Climate			
Mean annual precipitation from 2001 to 2006 (Schulz et al. 2010)	341 mm	238 mm	135 mm
Mean annual temperature (Schulz et al., 2010)	13.0 °C	14.2 °C	19.1 °C
Bioclimate (Oldeland et al. 2008)	Semi-arid cold	Semi-arid cold	Per-arid cool
Vegetation growth period	May – June.	March – April and September – October	March – April
c) Land use			
General	Silvopastoral use for sheep and goats, firewood collection	Pastoral use for sheep and goats, firewood collection	Pastoral use for goats
d) Herd			
Total number of sheep and goats in the studied villages	1000	350	370
Number of herds per village	17	2	2
Number of goats in the study herd	50	50	120
Identity of the herder	A member of the family (adult man)	Study herd: a member of the family (adult man) Other herds: several families join their animals and share the herding	A member of the family (shared between adult men and children)

2.3. Data analysis

2.3.1. Effect of the temporal resolution on the recorded distance

To analyze the effect of the recording interval (*I*) on the recorded daily walking distance (*D*), we chose the GPS data of Bou Skour, since they contained the longest time series with a 15 minute resolution (n=14570). From this data set, we created lower resolution subsets corresponding to recording intervals of 30, 45, 60, 75, 90, 105, and 120 minutes by omitting records. The recorded daily walking distance was then calculated using x/y coordinates for each day and averaged over the whole study period for each of the resolution subsets. In order to determine the functional relationship between recorded distance and recording interval, we applied non-linear regressions with STATISTICA 8.0 (StatSoft, Inc. 2007). Three different function types were compared: inverse, power and exponential, all continuously falling and approaching a lower limit, and each in two variants with the lower limit being either zero or a constant c (Table 2). We used the default setting of the program (loss function = $(\text{OBS–PRED})^2$; estimation method = quasi-Newton; convergence criterion = 0.0001; step width for all parameters = 0.5; starting values for all parameters = 0.1). When these settings did not lead to convergence, we used starting values previously established in similar situations until the iterations yielded a result. As the models differed in their complexity (1–3 fitted parameters + estimated variance), we used the Akaike Information Criterion corrected for small n (AIC_c; Burnham and Anderson 2002) for model selection, calculated in the ordinary least squares framework. As a goodness-of-fit measure, we present Akaike weights (w_i), which are the probability that a given model is the best among those compared (Burnham and Anderson 2002).

Table 2. Regression functions used for the analysis of the relationships between recorded daily walking distance (y) and recording interval (x) (all models) and between grazing intensity (y) and distance from the stable (x) (models with *). The letters a, b, and c denote fitted parameters.

Function name	Formula	Number of parameters
Inverse function*	$y = a / x$	1
Inverse function with constant	$y = a / x + c$	2
Power function*	$y = a x^b$	2
Power function with constant	$y = a x^b + c$	3
Exponential function*	$y = a \exp(b x)$	2
Exponential function with constant	$y = a \exp(b x) + c$	3

2.3.2. Spatial patterns of the grazing herds

For each site, we created circular vector grids of 3900 m radius around the stable using ArcGIS 9.3 (ESRI 2010). This defined radius corresponds to the maximum grazing distance at a 2 h interval found for any of the villages. The grid cells were 200 m × 200 m (4 ha) in size and the stable was positioned in the centre of the vector grid. Then, we counted the number of recorded GPS positions in each grid cell. Finally, we calculated the grazing intensities in each grid cell using the formula:

$$GI_{\text{herd},i} = n_i \times N_{\text{herd}} \times R \times D^{-1} \times GP^{-1} \times S^{-1}$$

with $GI_{\text{herd},i}$ [goats ha^{-1}] being grazing intensity of the herd in grid cell i; n_i the number of records within grid cell i; N_{herd} the number of goats in the herd; R the GPS recording interval (2 hours); *D* the daily grazing period (for this purpose we used a standard period of 12 hours); *GP* the total grazing period (number of days recorded) and *S* the area of the grid cell (4 ha).

We visualized the spatial grazing patterns of each of the three studied herds (GI_{herd}) using ArcGIS, both for the whole study period and for the separate seasons. We defined the seasons based on data availability. In Ameskar, we considered four seasons: spring (April–May), summer (June–August), autumn (September–November), and winter (December–January). In Taoujgalt, due to a lack of data from the winter months, we analyzed three seasons: spring (April–May), summer (June–August), and autumn (September–October). In Bou Skour, we considered four seasons: spring (March–May), summer (June–August), autumn (September–November), and winter (December–February). To help interpretation, we additionally plotted the topography of the study area with a 90 m digital elevation model provided by the National Aeronautics and Space Administration's Shuttle Radar Topography Mission (SRTM; Jarvis et al. 2006).

2.3.3. Grazing intensities around the villages

While GI_{herd} was used to describe the spatio-temporal grazing pattern of a particular herd, we applied GI_{village} to characterize the grazing intensities for the village as a whole. This allowed comparison between our three study sites as well as with published data. Underlying the calculation of GI_{village} is the assumption that the different village herds, while potentially using different sectors around the village, essentially follow the same distance decay function of grazing intensity.

Accordingly, we were only interested in the distance of the grid cells, not in their direction. We used the distance from the cell centroid to the stable, and assigned a value of 50 m to the central grid cell (instead of 0 m) as here the mean distance from stable to edge was approximately 50 m. We calculated GI_{villages}[animals ha^{-1}] as follows:

$$GI_{\text{village},i} = G_{I\text{herd},i} \times N_{\text{village}} \times N_{\text{herd}}^{-1}$$

with N_{village} being the total number of goats and sheep in the village (Table 1). In order to make the grazing intensities per village comparable, we grouped the grid cells into five distance classes (0–250 m, 250–500 m, 500–1000 m, 1000–2000 m, 2000–4000 m) and calculated mean GI_{village} values for each distance class. Then, we modeled the distance decay in *GI* with the same modeling approach and set of functions as those used for recorded distance vs. recording interval (see subsection 2.3.1 and Table 2). We only restricted our comparison to the three model variants without constants as GI_{village} should always approach zero for very high distances.

2.3.4. Daily trajectories of the goats

We analyzed the daily trajectories of the goats based on the GPS measured x/y coordinates, using all recording periods having been standardized to a recording interval of 2 h. In order to assess the daily walking distance, we summed the linear distances between each pair of successive points for each day, including the stable as the starting and end point of each daily trajectory. Likewise, we determined the daily maximum distance from the stable by calculating the linear distance of each point to the stable and then selecting the maximum distance. For both distances, we analyzed whether distances differed between seasons using one-way analyses of variance (ANOVAs), implemented in STATISTICA 8.0 (StatSoft, Inc. 2007), followed by HSD post-hoc tests for unequal N with $\alpha = 0.05$. Furthermore, we analyzed within-day trajectories, i.e. how the time of day influenced the distance from the stable using ANOVA.

3. Results

3.1. Effect of the temporal resolution on the recorded distance

Smaller GPS recording intervals (I) led to a significant increase in the recorded daily walking distance (D; Figure 2). For instance, the calculated distance increased by 18% when the recording interval was reduced from 2 h to 1 h. Among the six compared models, the exponential function with constant explained the relationship best (w_i = 94.6%), followed by the power function (w_i = 4.8%), while the four other functions were unsuitable. The equation of the best model was: $D = 3340 \times \exp(-0.0177 \times I/\text{min}) + 3953$. Using this function to extrapolate to a recording interval of 0 min (i.e. continuous recording) yielded a distance of 7293 m. The actual distance thus becomes 68% longer than the one recorded at two-hour intervals.

3.2. Spatial patterns of the grazing herds

Grazing patterns were distributed around the stables in the three villages (Figure 3). Generally, grazing intensities were highest in the immediate vicinity of the stables and showed a strong decline with distance. In both mountainous villages Ameskar and Taoujgalt, grazing was stretched up to the hills but not exceeding the hilltops, while in Bou Skour grazing was more concentrated south of the riverbed. In Ameskar the grazing pattern showed only a slight deviation from a radial distance decay, while in the other two villages, grazing was concentrated in certain directions, mainly north-south, while other directions were completely avoided.

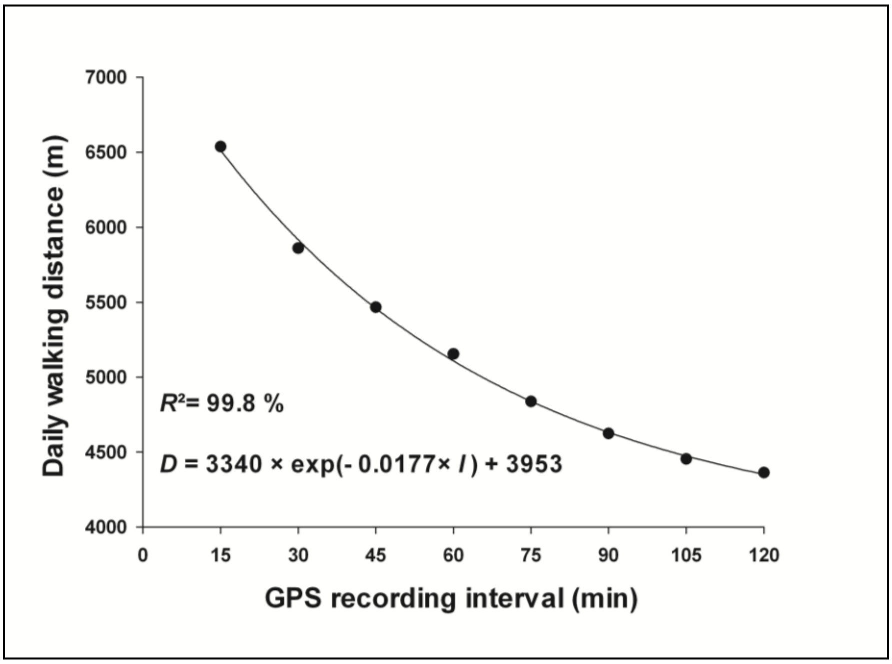

Figure 2. Dependence of the recording interval (*I*) [min] on the recorded daily walking distance (*D*) [m] for the collared goat in Bou Skour. Only the best-fitting regression function according to AIC_c is shown.

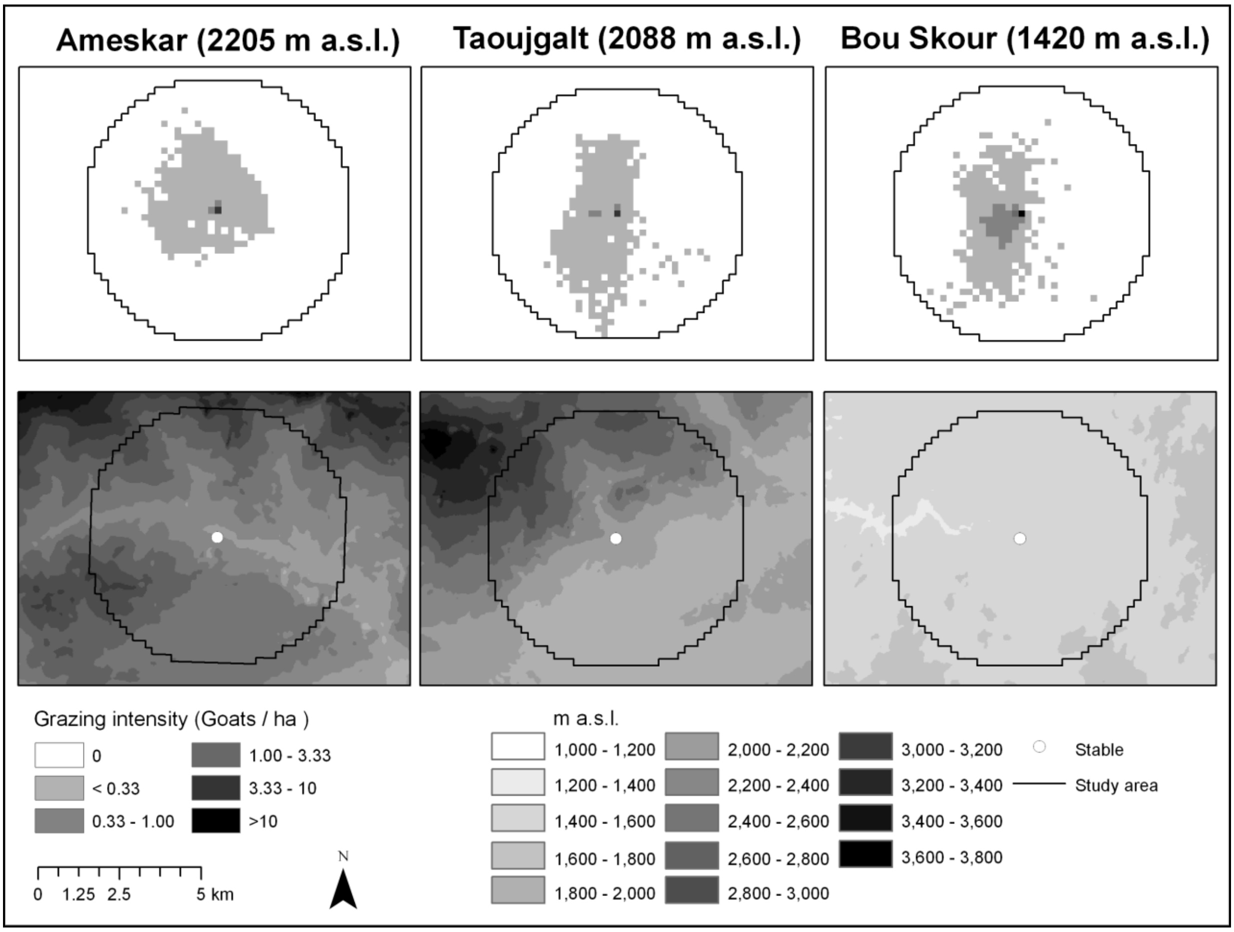

Figure 3. Grazing intensity patterns of the studied herds (GI_{herd}) of the three villages Ameskar, Taoujgalt, and Bou Skour (top row) in comparison with the topography of the sites (bottom row).

In Ameskar, the grazing range stretched further to the north and north-west, while visits to the south and south-east seemed to be avoided (Figure 3). The area visited by the herd differed little between seasons (Electronic Appendix 2). During autumn and summer, the herd was scattered over a slightly larger area than in winter and spring, with little variation in grazing intensities.

In Taoujgalt, the grazing intensity was highest in the valley north of the stable (village), while the rangelands east of the stable were mostly avoided by the herd (Figure 3). The grazing pattern varied between the seasons, such that in summer longer trajectories northwards and southwards were covered than in autumn and spring (Electronic Appendix 3). In spring, the herd moved mostly to the north and rarely to the south.

In Bou Skour, the grazing pattern extended to north-south direction with the highest grazing intensities in the west and south of the stable while the areas east were mostly avoided (Figure 3). The grazing area varied between the seasons, whereas little variation in grazing intensity was observed (Electronic Appendix 4). The areas visited in winter were limited in comparison to the other seasons and the northern part was mostly avoided.

3.3. Grazing intensities around the villages

At all three villages, $GI_{village}$ decreased continuously with distance from the stable (Table 3). For all distance classes, grazing intensities were highest in Ameskar. Grazing intensities were similar in Bou Skour and Taoujgalt, but differed across the distance classes. They were more than twice as high for Bou Skour within the first distance class (250 m radius around the stable), but then declined steeply to slightly lower levels than for Taoujgalt in the more distant areas.

Table 3. Mean grazing intensities in different distance classes around the stable (village), calculated for all animals (goats and sheep) of the respective village ($GI_{village}$).

Distance from the stable (m)	$GI_{village}$ [animals ha^{-1}]		
	Ameskar	Taoujgalt	Bou Skour
0–250	22.030	6.187	13.099
250–500	1.603	0.673	0.658
500–1000	0.809	0.436	0.495
1000–2000	0.387	0.141	0.132
2000–4000	0.012	0.009	0.004

For all three villages, the power function was the best among the three compared models (w_i = 67.8%–80.7%), followed by the exponential function (w_i = 19.3–32.2%), while the inverse function (i.e. a power function with fixed exponent of –1) performed poorly (w_i = 0.001%–0.5%) (Table 4). The exponent of the power function was highest for Taoujgalt (–1.69) and lowest for Bou Skour (–2.18) (Table 4), indicating the strongest distance decay of grazing intensity in the latter site.

Table 4. Best fitting regression functions of GI_{village} (in animals ha^{-1}) on distance D (in m). Among the three compared models (inverse function, power function, exponential function), the power function always performed best.

Study site	Function	R^2	w_i
Ameskar	$GI_{\text{village}} = 157287\ D^{-1.91}$	0.9767	80.7%
Taoujgalt	$GI_{\text{village}} = 17012\ D^{-1.69}$	0.9356	78.5%
Bou Skour	$GI_{\text{village}} = 291488\ D^{-2.18}$	0.9808	67.8%

3.4. Daily trajectories of the goats

The mean daily walking distance was 3580 m in Ameskar, 3480 m in Taoujgalt, and 4460 m in Bou Skour, based on the two-hour GPS recording interval. The daily walking distances varied significantly with season in all the three sites according to ANOVA (p < 0.001) (Figure 4). However, the post-hoc test revealed different homogenous groups within each site. In general, distances in spring and summer as well as in autumn and winter are more similar. The many outliers indicate that the distances also varied strongly within the seasons.

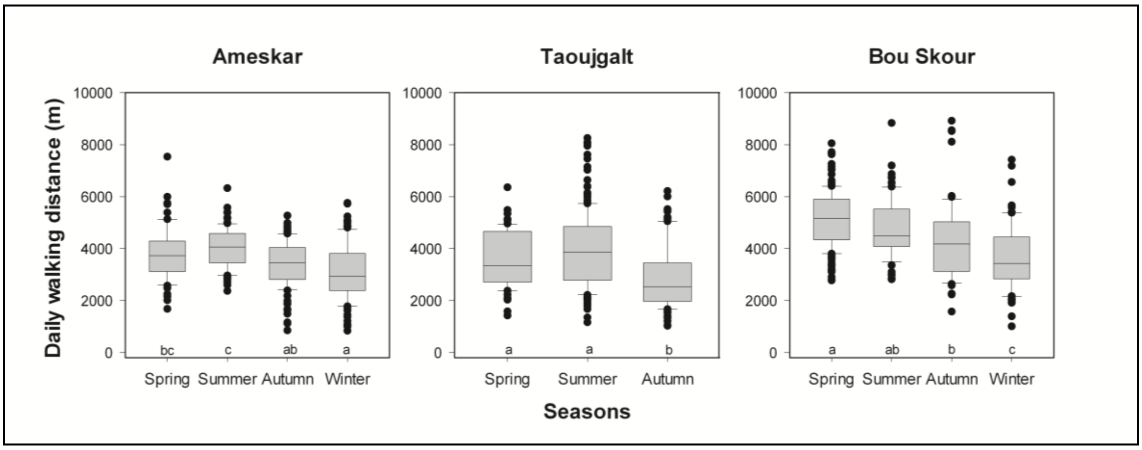

Figure 4. Seasonal variation in the daily walking distance recorded at a two-hour recording interval for each of the three sites. Medians, interquartile ranges, total ranges without outliers, and outliers are shown. All sites showed a significant variation between seasons according to ANOVA (p < 0.001). The letters under the box plots denote homogeneous groups according to the *post hoc* test.

In Ameskar and Taoujgalt, the mean daily walking distance was longest in summer and shortest in winter and autumn respectively. At both villages it reached a maximum of 4,000 m (June) and decreased to a minimum of 3,130 m in Ameskar and to 2,880 m in Taoujgalt. In Bou Skour, the mean daily walking distance showed a continuous decrease in mean daily walking distance from spring to winter. The longest mean daily walking distance of 5,130 m was registered in spring while the shortest distance of 3,680 m was registered in winter (note that these are the uncorrected values at a two-hour resolution; the true values are higher, see subsection 3.1).

The maximum daily walking distance from the stable varied significantly between the seasons at all three sites (Electronic Appendix 5). The patterns were quite similar to those of the mean daily walking distances at Ameskar and Taoujgalt (Figure 4). However, the patterns were not similar at Bou Skour. While the mean daily walking distance showed a decrease during the year, highest maximum distances from the stable were found in autumn. In Ameskar, the mean maximum distance reached its highest seasonal value of 1,700 m in summer and its lowest value of 1,340 m in winter. In Taoujgalt, the maximum distance from the stable was also longest in summer at 1,700 m and shortest in autumn at 1,250 m. In Bou Skour, the maximum distance from the stable reached the highest seasonal mean of 1,760 m in autumn and the lowest mean value of 1,450 m in spring.

The daily trajectories of the goats of the three villages started in the morning at about 8 hours (or between 6 and 8 hours in the case of Bou Skour) and ended at about 20 hours (Figure 5). Distances to the stable over time followed a unimodal distribution in Ameskar and Taoujgalt with a peak at 14 hours. The longest mean distance from the stable during the day reached about 1,500 m in Ameskar and Taoujgalt. In Bou Skour, the distance from the stable reached a plateau of about 1,000 m between 12and 16 hours. While the mean trajectories followed a clear pattern, there was much variation among the days in all three sites, indicated by the high standard deviations. For example, in Ameskar at 12 hours, the distance from the stable ranged from less than 700 m to more than 1,500 m.

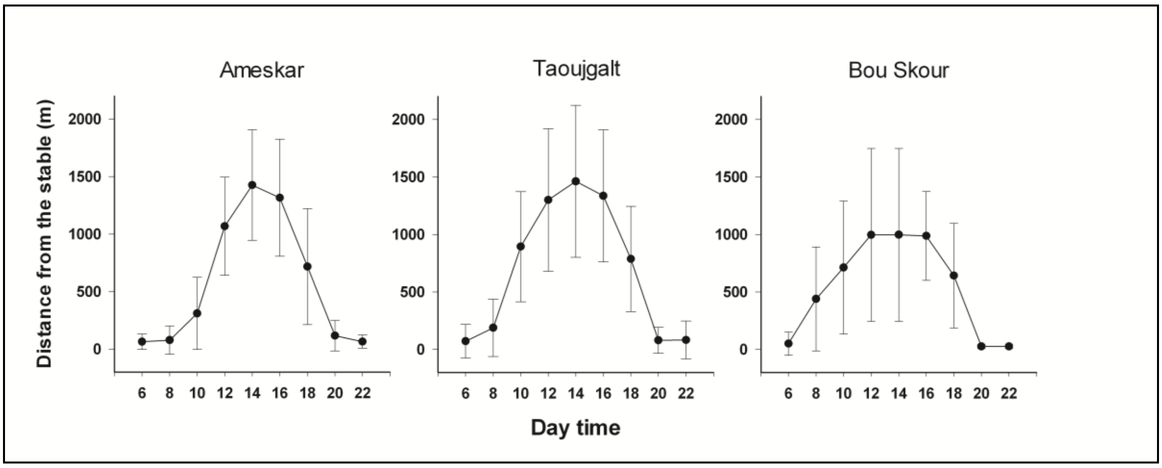

Figure 5. Mean within-day trajectories of the studied goat herds in the three sites. The error bars represent the standard deviation. For all three villages, the ANOVAs yielded significant temporal pattern ($p < 0.001$).

4. Discussion

4.1. Effect of the temporal resolution on the recorded distance

The detected negative effect of lower temporal resolution (i.e. higher recording interval) on the recorded walking distance was expected as the trajectories are inevitably shorter when fewer GPS points are connected (see also Pépin et al. 2004; Johnson and Ganskopp 2008). For cattle in the Great Plains, USA, Johnson and Ganskopp (2008) found a decrease of more than 50% in the estimated travelling distance between 5 and 160 minute recording intervals. Based on our regression function, the decrease would be slightly more than 40% between the same recording intervals (5 and 160 minute) for the goats in Bou Skour: a remarkably similar result given the different livestock species and countries. As in Johnson and Ganskopp (2008), the exponential decay function with a constant proved to be the best model in our case. These authors did not explicitly state which functions they compared and which statistics they used for model selection, so that the reliability of their results is difficult to assess. Our approach, however, allows us to have confidence in the results, using information criteria and taking into consideration six reasonable decay functions. The best fitting functions in both cases had a constant. This constant corresponds to the limit of spatial distance between two points of the trajectory as the temporal distance increases. This value (in our case 3953 m) therefore represents the mean distance between two random points within the grazed area (weighted by the frequency of visit).

Determining the regression function between GPS resolution and recorded daily walking distance of livestock is important since it allows extrapolation from discontinuously recorded data to continuous data which is the length of the actual trajectory. Furthermore, this regression approach allows the comparison of data produced in different studies of varying temporal resolution (see subsection 4.4). We therefore recommend conducting similar pilot studies on the effect of temporal resolution on recorded travelling distance prior to any GPS based investigation of the length of livestock travelling trajectories. The establishment of regression functions from such pilot studies provides reliable estimates of actual trajectory lengths even with rather long recording intervals, thus enabling longer recording periods without battery change. However, a sound statistical approach is needed for the determination of reliable regression functions. This should involve the comparison of different reasonable functional models, their direct fitting with non-linear regression (instead of using problematic transformations of the axes to apply linear regressions), and model selection with state-of-the-art methods.

4.2. Spatial patterns of the grazing herds

Grazing intensity varies according to the movements of the animals and their spatial distribution, which depend on many factors such as the availability, distribution and composition of forage (Adler and Hall 2005; van Beest et al. 2010). High grazing intensities around water points have been found in many studies of livestock behavior (Andrew 1988; Alder and Hall 2005; Todd 2006). In the case of tended herds, we found that stables or home village of the herder also show high grazing intensities in the vicinity.

However, the spatial grazing patterns differed between the herds in our study. In Ameskar, grazing was more extended to the north and limited to the south. This is due to rugged topography or steep slopes limiting access to the southern areas. In contrast, the northern areas consist of moderate slopes with vegetation, including juniper trees and many chamaephytes, of high forage value for goats (Malan 2000). The eastern limit of the grazing area is defined by village boundaries (personal observation MF).

In Taoujgalt, grazing occurred mainly in a north-south direction from the upper slopes to the north and west to the plain in the south. On the north and western hill slopes are good fodder species for goats: juniper trees and several dwarf shrub species while in the plain *Artemisia* species and other dwarf shrubs have valuable biomass (Akasbi et al. 2012 b). The eastern part was avoided because it was used by other herds, i.e. sedentary herds of the neighboring village and some transhumant herds (personal observation MF).

In Bou Skour, grazing also showed a north-south direction with a higher grazing intensity in the west to south-west. This pattern arose due to the fact that the herd do not go too far away from the stable in winter due to the cold weather that affect walking ability of the goats (herder's observation), thus leading to the higher grazing intensities in the hills southwest of the village. The area to the south-east and east was determined by sharp boundaries between different community members' lands along a riverbed. The herder avoids grazing his animals on a neighbor's land according to the grazing rules in this village (personal observation MF).

Several factors could influence the seasonal changes in the distribution of grazing such as precipitation, temperature and fodder availability (e.g. Güsewell et al. 2007; Putfarken et al. 2008). In Ameskar, a slight seasonal variation was observed in grazing areas and grazing intensities. During summer and autumn, the herd used a slightly larger area than in spring and winter. This limited movement in spring and winter could be due to the harsh environmental conditions on the mountain ridges during these seasons. In Taoujgalt, the herd visited an area twice as large during summer in comparison to the other seasons. In spring, the herder used rather the hill slopes offering abundant shrub species than the sagebrush plain south of the village used in spring by transhumant pastoralists as transition rangeland before migrating into the high mountain rangelands at the end of May (Akasbi et al. 2012 a). In contrast during summer and autumn, when the transhumants pastoralists visited other rangelands, he also used the plain which offers a biomass peak of flowering *Artemisia herba-alba* (Gresens 2006). Larger used areas in summer than autumn could be explained by the length of the days that allow in summer for longer grazing periods per day. In Bou Skour, by far the most arid of the studied sites, the grazing area was larger during summer than in other seasons probably due to the lack of vegetation resources in the dry season. The northern part was mostly avoided in winter, perhaps due to the temporary presence of some transhumant pastoralists who use this territory as winter rangeland (Akasbi et al. 2012 a).

4.3. Grazing intensities around the villages

Grazing intensities were generally higher in Ameskar than in both other sites, reflecting the fact that its herd was almost three times bigger (Table 1). We found grazing intensities ranging from 0.004 animals ha^{-1} at distances greater than 2000 m from the stable, and up to 22 animals ha^{-1} within 250 m radius around the stable (Table 3). In close proximity to the stable it was even higher (Table 4). Kawamura et al. (2005) reported for Inner Mongolia, China, a grazing intensity between 0 and 72,048 SU ha^{-1} (SU = sheep unit), but the recording interval (1 min) was not taken into account. From their daily recording time of 15 h, the 60 records per hour, and the fact that one goat corresponds to 0.8 SU, we can recalculate that their maximum value was actually 64 goats ha^{-1}. Thus, the maximum grazing intensity in Inner Mongolia is three times higher than that of Ameskar, four times higher than that of Bou Skour and ten times higher than that of Taoujgalt (Table 3). A study of comparable ecosystems in southern Africa – Soebatsfontein with 146 mm and Gellap Ost with 153 mm mean annual precipitation – yielded grazing intensities of 0.07 and 0.06 SSU ha^{-1} (SSU = small stock unit, i.e. one sheep or goat), respectively (Haarmeyer et al. 2010). In south-eastern Spain, Robles and Passera (1995) studied the carrying capacity of a farm in a mountainous area with 324 mm mean annual precipitation. They found values ranging between 0.63 goats ha^{-1} and 0.92 goats ha^{-1}. From these comparisons we conclude that the grazing intensities in the first 250 m radius of our study sites are very high. This is further supported by the investigation of Alaoui (1985) on the effect of three grazing intensities on sagebrush steppe in the upper Moulouya, being an area very similar (Altitude: 1800 m a.s.l., mean annual precipitation: 226 mm, mean annual temperature: 14.1 °C) to the general conditions at the Taoujgalt site in our study. He considered 0.7 ewes ha^{-1} as a low grazing intensity, 1 ewe ha^{-1} as moderate and 3 ewes ha^{-1} as high. These grazing intensities correspond to the rate of plant consumption of 30%, 40%, and more than 50% of the standing biomass per hectare, respectively (Alaoui 1985). Consequently, we conclude that grazing intensity is very high within a radius of 250 m at our three sites, moderate in the zone of 250–500 m around Ameskar and low at more than 500 m distance from Ameskar and at more than 250 m in the other two sites (Table 3).

Manthey and Peper (2010) mathematically derived a null model for grazing intensity around stables: assuming that the animals generally move in a radial fashion and at constant pace away from and back to the stable, grazing intensity will be an inverse function (i.e. a power function with exponent –1). They studied the effects of grazing such as dung density (not grazing intensity directly) in mountain rangelands of Azerbaijan, comparing the inverse and three other functions, and reported best fits for the inverse function. While they did not include the general power function – the superior function in our study – in their comparison, their figures indicate that in their case a power function with exponent –1 was indeed a reasonable model. However, in our Moroccan study systems, the inverse function was not at all adequate. The exponents determined for the best fitting power models with values ranging from –1.69 to –2.18 indicate that here the distance decay is much stronger than expected by the null model. This means that grazing is extremely clumped around the stables. With this in mind, we propose the ratio of the actual exponent to the theoretical exponent from the null model (–1) as a measure of grazing concentration (*GC*) around stables and similar hotspots. A *GC* above 1 thus indicates unexpected clumping and a *GC* below 1 an overdispersion. With *GC* = 2.18, the strongest clumping of livestock activities was detected around the stable in Bou Skour. This might be due to the fact that the owner of the herd in Bou Skour lives in an isolated house far from his neighbors. He opens the stable at sunrise and lets the goats roam freely around the house before the tended daily itinerary starts at about 8 hours, while in Taoujgalt and Ameskar the herdsmen directly leave the village with the herd.

4.4. Daily trajectories of the goats

In Ameskar and Taoujgalt, the mean daily walking distance was longest in summer, while in Bou Skour it was longest in spring. This could be explained by the difference in climatic conditions (Electronic Appendix 1.a-c) and the resulting fodder availability in each village. In Ameskar, higher fodder availability in summer and longer days led to longer distances in this season. Similarly in Bou Skour, longer walking distances in spring were mainly due to the high fodder availability in this season (herder's statement). However, in Taoujgalt longer distances in summer were mainly due to the length of the day and less competition by other herds in this season. The herd thus walked long trajectories from the north to the south. The shortest distances were registered in winter in Ameskar and Bou Skour while in Taoujgalt, it was in autumn. However, in the last village the data were missing for winter. We think that also in this case the same pattern will occur in winter if the data were available. The shortest distances in winter are mainly due to (i) the very cold weather in this season that limit goat's walking ability (herder's observation) and to (ii) the short day length that led to shorten the herding time. Other studies in other semi-arid ecosystems also found such seasonal differences in walking distances. Lachica et al. (1999) found in southern Spain that the distances travelled by goats were longest in summer and shortest in autumn due to fodder availability. Schlecht et al. (2009) found in northern Oman that goat walking distances in spring were longer than those in autumn. Similarly to our study, she reported that the distance was longer with higher fodder availability. Hence, depending on the climatic situation within the herders' territory, fodder availability and climatic conditions control the mean daily walking distances in the seasons.

We found mean daily walking distances between 3,480 and 4,460 m for the three study sites, based on the two-hour temporal resolution of our GPS records. Applying the ratio of trajectory length under continuous recording vs. the two-hour interval from Bou Skour (1.68), these values would translate to actual daily walking distances of 5,840 to 7,490 m. In northern Oman (Schlecht et al. 2009) as well as in western Niger (Schlecht et al. 2006), the daily walking distances of goats were higher than in Morocco. In the first case, they varied between (10,500–16,700 m) and in the second case between (6,200–11,800 m) based on a five-second GPS recording interval in both studies. The high itineraries in northern Oman are because the goats had to walk 4000–5000 m before they reached the first grazing area (Schlecht et al. 2009). By contrast, our values are higher than those of Sharma et al. (1998) from northern India, who reported daily walking distances for goats between 3,800 m and 5,000 m. In this case, the lower values are probably due to difference in grazing system which was free ranging vs. herded grazing in our study. This is in line with other studies that showed that free grazing animals walk shorter distances than the herded ones (Schlecht et al. 2006). It seems that the differences in trajectory lengths between the different regions are driven by many factors. The most important are varying fodder availability, climatic conditions (i.e. temperature) and the grazing system. Hence, rangeland managers should take into account the difference between ecosystems, i.e. seasonal variation in fodder availability and climatic conditions in order to provide the most adequate strategies for each region.

The maximum distance from the stable in Ameskar and Taoujgalt followed the same pattern as that of the mean daily walking distance, while in Bou Skour the pattern was different. Concerning the first two villages, the same reasoning of the daily walking distance (see previous 2 paragraphs) could be applied here. In Bou Skour, while the longest mean distance occurred in spring, the longest maximum distance from the stable occurred in autumn. This could be explained by the fact that the herd in Bou Skour walked long distances in spring but within a small radius from the stable because of high fodder availability in the area. However, in autumn fodder availability decrease and thus the herd reach far areas to look for sufficient fodder.

The mean distance from the stable at midday was much lower in Bou Skour than in the other two sites (see Figure 5) despite the longer daily trajectories there. This could be explained by the fact that in Ameskar and Taoujgalt, the herds left the stable and did not go back home during the day until evening, whereas in Bou Skour the herder frequently returned home with his herd at midday in summer for lunch and to avoid the peak of hottest temperatures. This is in line with Schlecht et al. (2009) who showed that during the dry season the trajectories of the goats shortened and the resting periods lengthened at Al Jabal Al Akhdar in northern Oman. We conclude that trajectory length of the tended herds depends on the climatic conditions of the ecosystem and thus rangeland managers should provide adequate strategies for different bioclimatic regions.

5. Conclusions

This study provided the first comprehensive and detailed description of the spatial and temporal grazing pattern and intensity of tended goats in southern Morocco. We found significant differences in the mean walking distance and the maximum distance from the stable between seasons. This seasonal pattern was similar between Ameskar and Taoujgalt, while it was different in Bou Skour. In the first two villages with similar climatic conditions, the distances were longest in summer while in Bou Skour they were in spring while they were shortest in winter or autumn. This variation seems to be driven by fodder availability, temperature (cold or hot weather) and length of the day. Grazing intensities were highest in the first 250 m from the stables. Some places were avoided because of grazing rights in the village, village boundaries, topographical barriers or difficult terrain access (e.g. steep slopes). Further, our paper contributes in two ways to methodological advancement within rangeland ecological studies in general. Firstly, we made a statistically sound proposal for how to derive actual trajectory lengths from GPS records of different resolution. Secondly, we developed a statistical framework for the assessment of the distance decay of grazing intensity around hotspots (such as stables or water points), proposing grazing concentration as a metric to assess the deviation from the null model proposed by Manthey and Pepper (2010). In both aspects, we have built on recent literature to develop new state-of-the-art methods. In order to confirm the findings and to generalize them to the whole region, similar analyses of sheep would be helpful to identify both differences and similarities in grazing patterns. For a better interpretation of grazing pattern and intensity data, we recommend their combination with vegetation or biomass data as a next step. This would help assess land use pressure on these rangelands and develop sustainable utilization and management programs.

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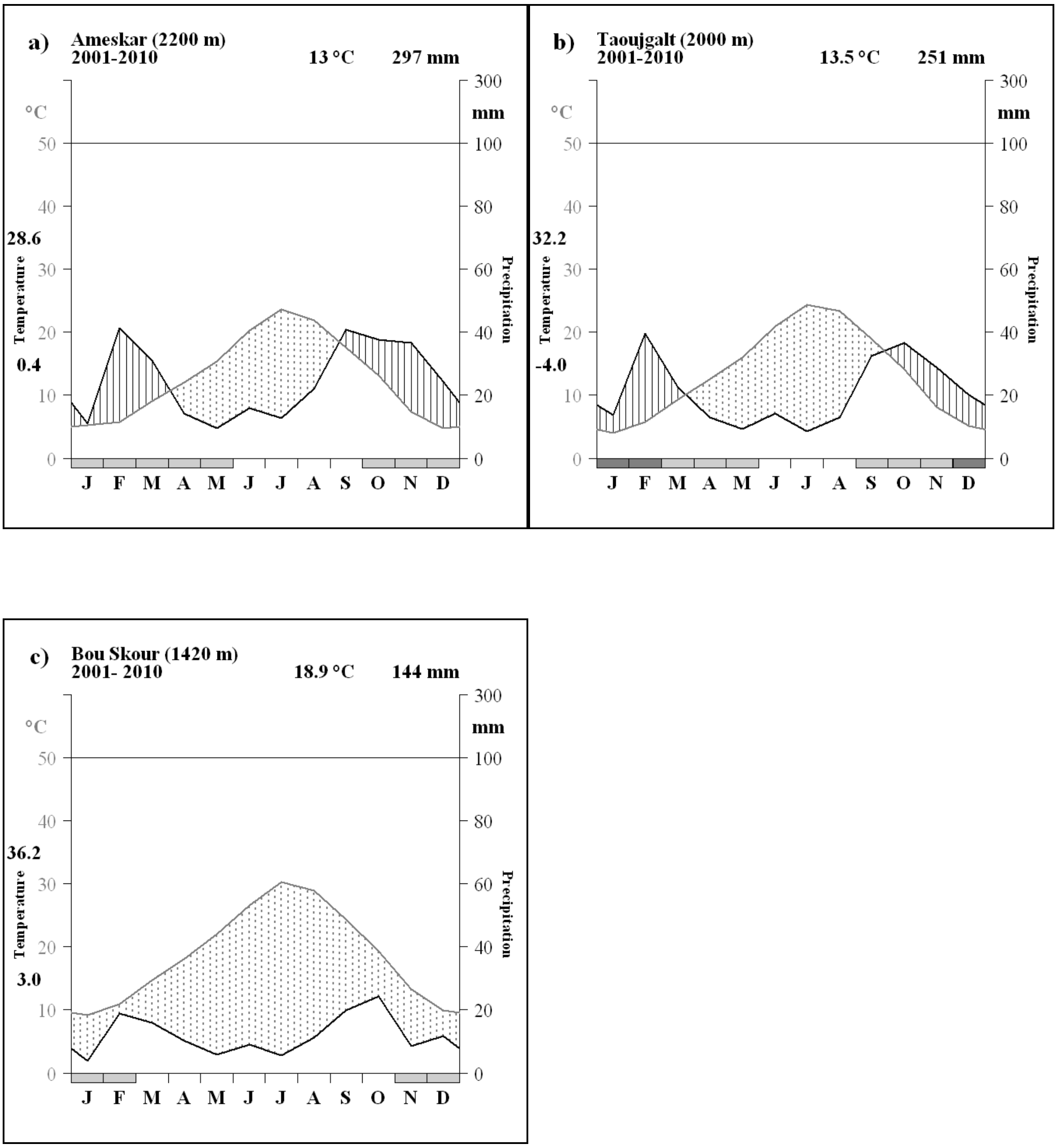
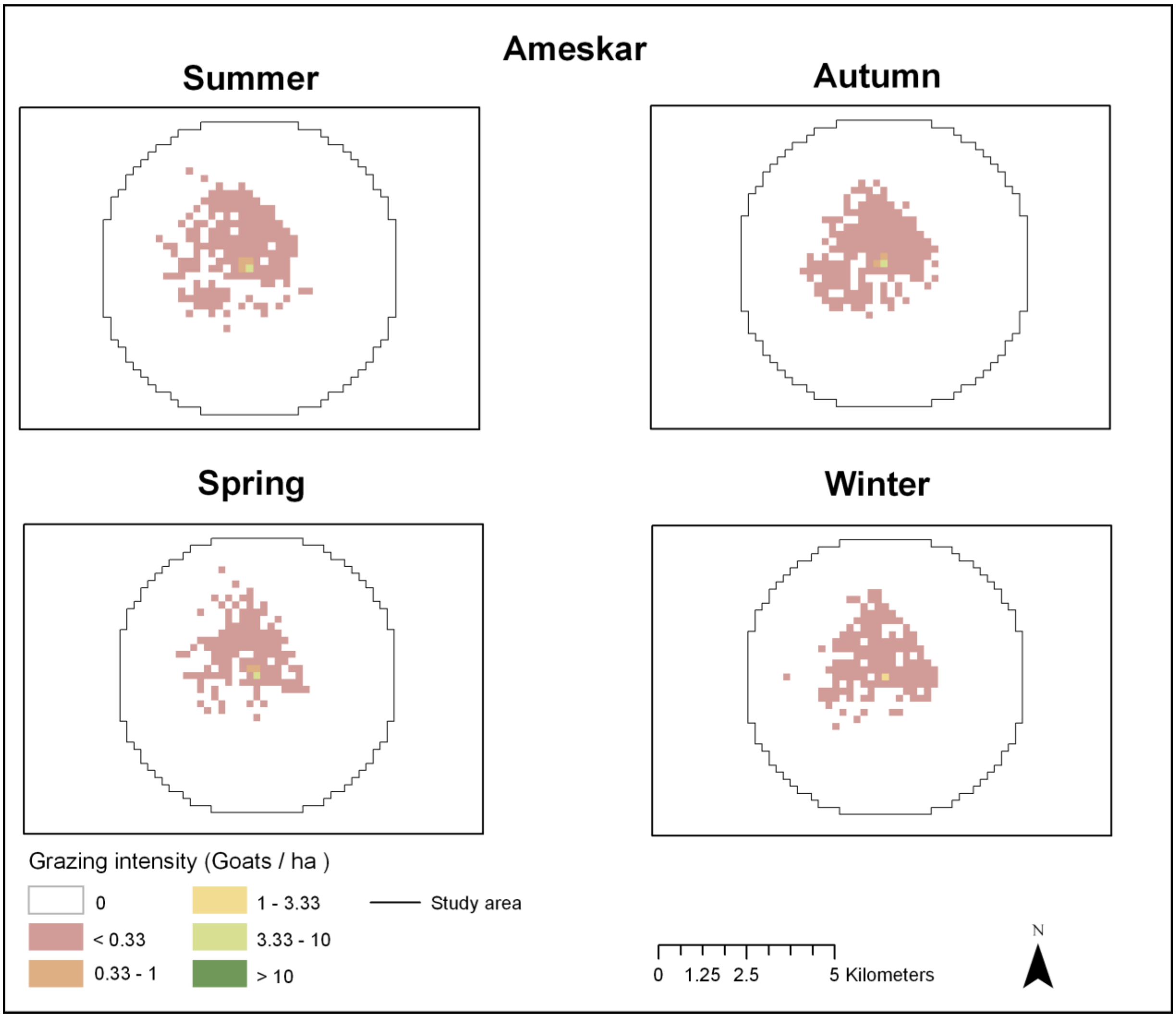
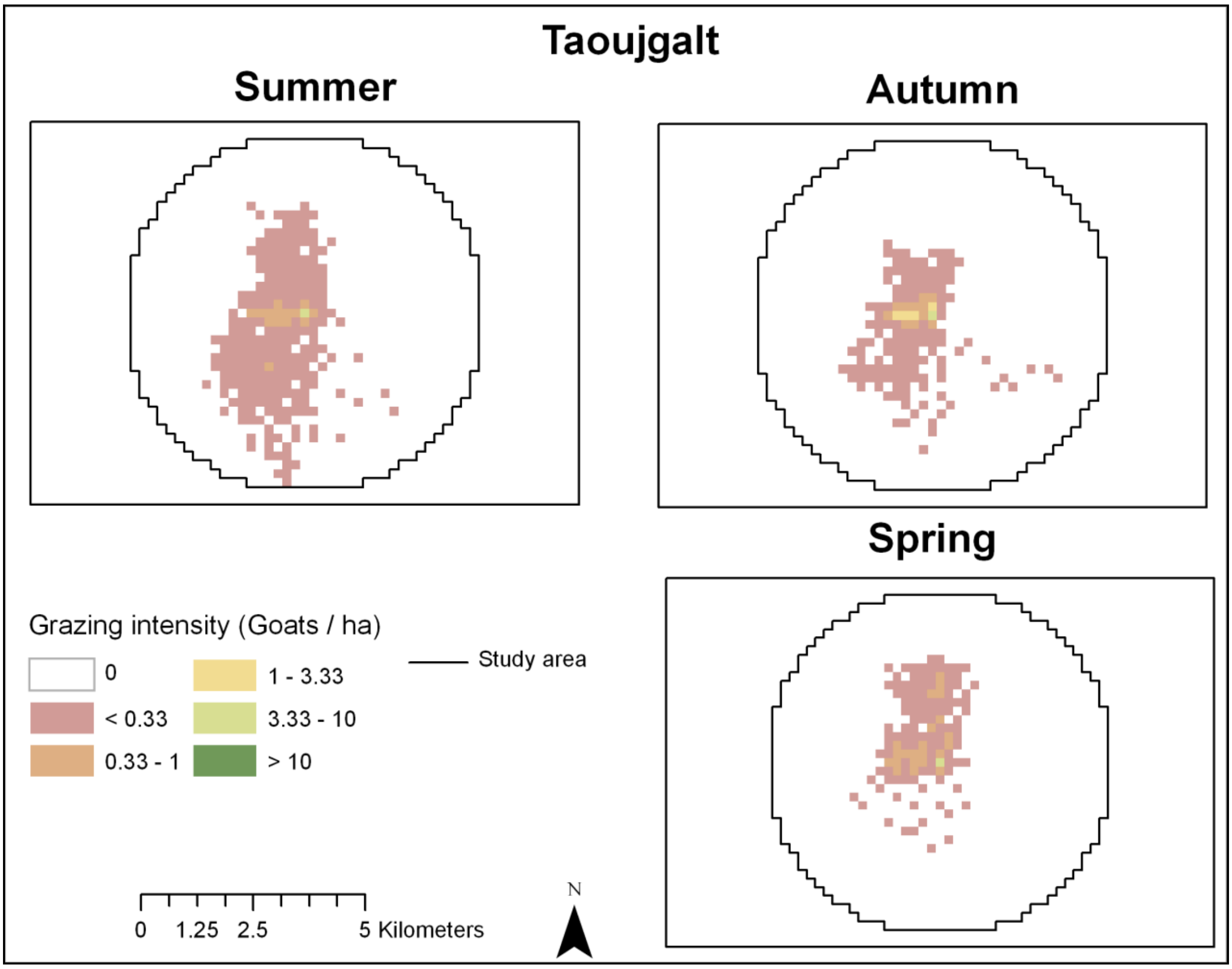


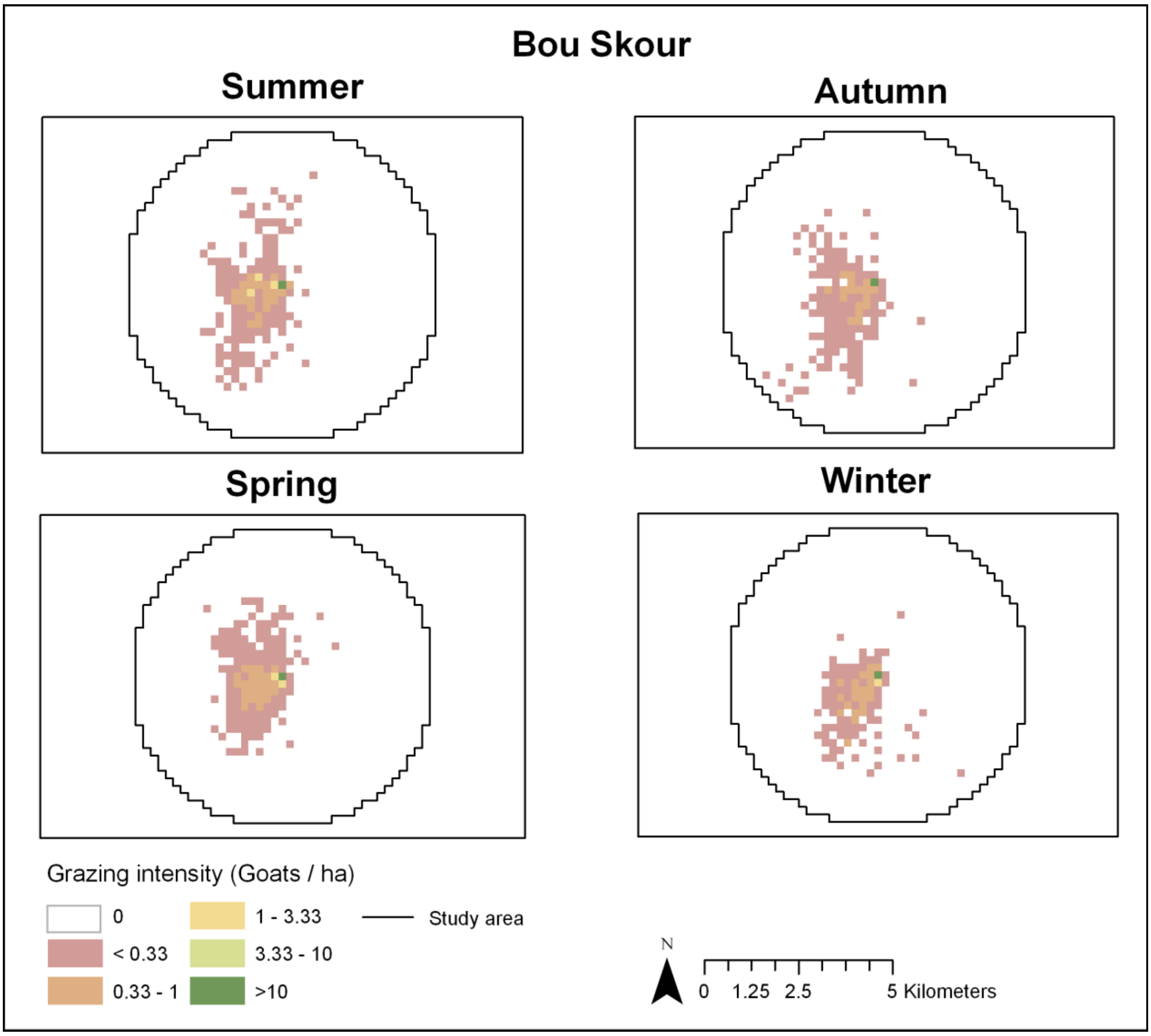
Electronic Appendix 1. Walter-Lieth diagrams of the three sites for a ten-year period. The numbers above the figures represent the mean annual temperature and the mean annual precipitation. The black curve represents precipitation in millimeters and the grey curve represents temperature in degree Celsius. Dotted areas represent an arid season, while the area with bars represents a humid season. The upper number on the left y-axis equals the mean daily maximum temperature of the warmest month, and the lower number the mean daily minimum temperature of the coldest month. The rectangles below the x-axis represent the period of sure frost (dark grey) and a period of probable frost (light grey).



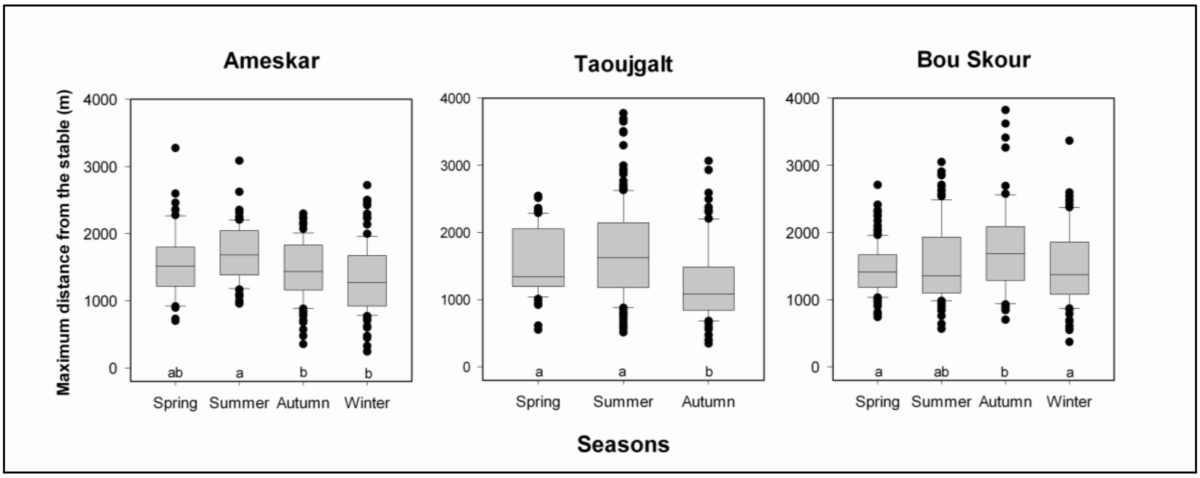
Electronic Appendix 2. Seasonal grazing patterns in Ameskar.



Electronic Appendix 3. Seasonal grazing patterns in Taoujgalt.



Electronic Appendix 4. Seasonal grazing patterns in Bou Skour.



Electronic Appendix 5. Seasonal variation in the daily maximum distance from the stable for each of the three sites. All sites showed a significant variation between seasons according to ANOVA ($p < 0.001$). The letters under the box plots denote homogeneous groups according to the *post hoc* test.