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PAR
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AUGMENTATION RÉCENTE DU COUVERT LIGNEUX ÉRIGÉ DANS LES ENVIRONS DE KANGIQSUALUJJUAQ (NUNAVIK, QUÉBEC)

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AVANT-PROPOS

Ce mémoire de maîtrise en sciences de l'environnement représente l'aboutissement de mes recherches menées au cours des années 2007 à 2009 dans les environs du village de Kangiqsualujjuaq (Québec nordique), sous la direction du Dr. Esther Lévesque de l'Université du Québec à Trois-Rivières. Il comprend deux chapitres. Le premier constitue un résumé substantiel de mon projet de recherche, présenté en français. Il est formé des sections suivantes : introduction, problématique, objectifs, méthodes, résultats, conclusions et bibliographie. Le second chapitre est rédigé en anglais sous forme d'article scientifique, intitulé « Recent expansion of erect woody vegetation in the Canadian Eastern Low Arctic ». Il s'agit d'une synthèse de mes résultats de recherche portant sur les changements dans le couvert végétal de la toundra environnant le village de Kangiqsualujjuaq en réponse au réchauffement climatique récent. Le manuscrit sera soumis pour publication dans la revue *Arctic, Antarctic and Alpine Research*. J'en suis l'auteur principal; ma directrice Esther Lévesque ainsi que Stéphane Boudreau de l'Université Laval sont co-auteurs.

Ce mémoire est complété par trois annexes. Les deux premières sont des illustrations démontrant l'augmentation récente du couvert ligneux érigé (arbustes érigés et arbres) dans le site à l'étude. La troisième annexe présente les directives aux auteurs de la revue *Arctic, Antarctic and Alpine Research*.

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RÉSUMÉ SUBSTANTIEL

1.1 Introduction

L'Arctique se réchauffe et change. Un peu partout dans les régions nordiques, les écosystèmes subissent des modifications plus ou moins importantes à plusieurs niveaux, ce qui est attesté autant par les résultats de multiples études scientifiques (Keeling et al., 1996; Serreze et al., 2000; Sturm et al., 2003; Hinzman et al., 2005) que par le savoir écologique des habitants du Grand Nord (Nickels et al., 2002; Thorpe et al., 2002). Une des réponses fonctionnelles majeures des écosystèmes terrestres suite au réchauffement du climat est la modification du couvert végétal (Levis et al., 1999; Kittel et al., 2000; Beringer et al., 2005; Tape et al., 2006). Les arbustes érigés (≥0,5 m) sont parmi les plantes de toundra qui répondent le plus au changement environnemental, ce qui les rend particulièrement importants pour les écosystèmes nordiques (Bret-Harte et al., 2002). Il n'est donc pas surprenant que la zone de transition entre la toundra herbacée et la toundra arbustive réponde le plus rapidement au réchauffement actuel (Epstein et al., 2004). Lors d'études expérimentales visant à évaluer les réponses à court terme de la toundra arctique face à des réchauffements atmosphériques légers imposés par l'installation de serres ouvertes, les arbustes érigés ont réagi, parfois de façon remarquable, par le biais d'une croissance accrue et de la fermeture du couvert par les plants préétablis (Chapin et al., 1995; Chapin et Shaver, 1996; Hobbie et Chapin, 1998; Bret-Harte et al., 2001, 2002; Van Wijk et al., 2003; Jonsdottir et al., 2005; Wahren et al., 2005; Walker et al., 2006). Cette réponse au réchauffement expérimental était accompagnée d'effets délétères sur les éléments non vasculaires du couvert végétal (Walker et al., 2006). Des données expérimentales récentes suggèrent par ailleurs que l'augmentation du couvert arbustif pourrait favoriser le recrutement d'espèces arborescentes telles que les épinettes noire (*Picea mariana* (Mill.) BSP) et blanche (*P. glauca* (Moench) Voss) dans la zone de transition entre la toundra forestière et la toundra arbustive (effet de facilitation; Cranston et Hermanutz, en prép.).

Une augmentation du couvert d'arbustes érigés a des conséquences importantes sur plusieurs facteurs écologiques. Elle altère l'équilibre énergétique en réduisant l'albédo et en haussant le flux de chaleur sensible vers l'atmosphère et le sol (Sturm et al., 2005a). Elle altère aussi l'équilibre chimique, au niveau du carbone via des changements dans la production et le stockage du matériel ligneux, en retenant davantage les débris organiques en transit (Fahnestock et al., 2000) et en stimulant une plus grande décomposition hivernale, la température du sol étant plus élevée sous la neige retenue par les arbustes (Grogan et Chapin, 2000; Schimel et al., 2004; Sturm et al., 2005b). Enfin, elle altère l'hydrologie en haussant l'évapotranspiration estivale ainsi que la quantité de neige retenue en hiver, et en modifiant la profondeur du mollisol et ses caractéristiques hydrauliques (Sturm et al., 2001a; Pomeroy et al., 2006; Strack et al., 2007). Sturm et al. (2001b) et Beringer et al. (2005) suggèrent d'ailleurs qu'une expansion panarctique du couvert arbustif créera une rétroaction positive qui résultera en un réchauffement supplémentaire de l'Arctique.

Les liens qui unissent une hausse du couvert arbustif et la faune, dont le caribou qui constitue globalement le principal brouteur de la toundra arctique, sont mal compris et peu documentés. Un des liens est bien entendu celui des ressources alimentaires qui, si modifiées par les changements climatiques, auront un impact sur la dynamique des populations (Lenart et al., 2002). Le bouleau glanduleux (*Betula glandulosa* Michx.) représente l'une des principales espèces composant le régime alimentaire du caribou (Crête et al., 1990) et le saule laineux (*Salix lanata* L. *sensu lato*, *i.e. S. calcicola* Fern. & Wieg. et *S. richardsonii* Hook.) constitue dans certains cas une part substantielle de sa diète estivale (Ouellet et al., 1994). Une analyse récente des cernes de croissance de saules laineux provenant de la toundra arctique russe a d'ailleurs révélé une croissance accrue de cette espèce durant les 60 dernières années (Forbes et al., sous presse). Il semble donc que l'expansion de certaines espèces ligneuses érigées comme le bouleau glanduleux et les saules puisse être bénéfique pour le caribou, bien que la hauteur et la densité du couvert puissent éventuellement influencer leurs déplacements et entraîner une modification des routes migratoires.

Sur le plan humain, un couvert arbustif plus abondant, plus dense et plus haut peut entraver les déplacements des habitants du Nord et nuire aux arbrisseaux producteurs de petits fruits charnus, diminuant leur disponibilité pour l'alimentation et affectant les aires traditionnelles de récolte.

Les évidences d'une expansion du couvert arbustif dans l'Arctique sont peu nombreuses et souvent anecdotiques. À notre connaissance, la seule étude à démontrer clairement une augmentation récente de ce type de couvert tout en fournissant des données précises sur l'ampleur du changement et sur les espèces responsables est celle de Tape et al. (2006). Ces auteurs ont documenté une augmentation substantielle des arbustes érigés durant les 50 dernières années sur 320 km^2 de paysages arctiques en Alaska. Des évidences indirectes d'une augmentation récente des arbustes érigés dans l'Arctique proviennent d'analyses d'images satellitaires qui démontrent une hausse constante du Normalized Difference Vegetation Index (NDVI) dans les latitudes nordiques de l'Amérique du Nord au cours des 20 dernière années (Myneni et al., 1997; Goetz et al., 2005). Dans la toundra, cet indice augmente de façon constante et uniforme en fonction de l'abondance des arbustes (Jia et al., 2004). Par ailleurs, une migration relativement récente de la limite des arbres vers le nord est rapportée par plusieurs auteurs, notamment en Alaska (Cooper ,1986; Rowland, 1996; Suarez et al., 1999; Lloyd et al., 2002; Lloyd et Fastie, 2003), au Manitoba (Scott et al., 1987; Scott et Hansell, 2002), au Québec (Gamache et Payette, 2004, 2005) ainsi qu'en Russie (Shvartsman et al., 1999). Puisque cette remontée de la limite des arbres semble résulter de conditions climatiques plus chaudes (Shvartsman et al., 1999; Gamache et Payette, 2004; Hinzman et al., 2005), on peut s'attendre à ce que, dans ces régions, les éléments arbustifs du couvert végétal répondent eux aussi positivement.

1.2 Problématique

Considérant l'ensemble des impacts écologiques et sociaux pouvant découler d'une augmentation du couvert ligneux érigé dans les écosystèmes nordiques, il apparaît critique de documenter adéquatement l'étendue et la nature de ce type de changement dans la toundra arctique. Si une telle évolution du couvert végétal est en cours à large échelle, elle a probablement déjà commencé à influencer les budgets de chaleur et de CO_2 dans les régions nordiques, peut-être à un niveau comparable à celui associé à la diminution de l'étendue de la glace marine (Hinzman et al., 2005; Tape et al., 2006). Or, il existe très peu d'études à échelles fines qui ont examiné les changements différentiels dans les types de végétation et entre les régions de l'Arctique (Jia et al., 2003). La nature et l'ampleur de l'augmentation du couvert ligneux érigé demeurent inconnues pour la majorité de l'Arctique, et tel est le cas pour l'est de l'Arctique canadien. À l'exception d'indices tels qu'une avancée apparente de la limite des arbres (Gamache et Payette, 2005), des changements contemporains du couvert ligneux érigé dans la toundra de cette région de l'Arctique restent à démontrer et à documenter.

1.3 Objectifs

1.3.1 OBJECTIF GÉNÉRAL

Étudier un secteur stratégique de l'est de l'Arctique canadien afin de déterminer s'il est l'objet de changements contemporains du couvert ligneux érigé. Le cas échéant, caractériser la nature et l'ampleur de ces changements.

1.3.2 OBJECTIFS SPÉCIFIQUES

1) Vérifier la disponibilité des outils photographiques et des données nécessaires à l'analyse du changement de couvert végétal dans un secteur-clé de l'est de l'Arctique canadien et statuer sur la possibilité d'effectuer une telle analyse. Dans la négative, en déterminer les causes.

2) Dans l'éventualité où des changements sont détectés, les quantifier en termes de surfaces nettes et de pourcentage relatif de changement par rapport aux années de référence en fonction des outils disponibles. Dans le cas contraire, évaluer les limites des approches utilisées.

3) Classifier les changements observés en fonction des divers habitats et attributs physiques du milieu (exposition, topographie, altitude) et évaluer l'importance relative des changements selon ces habitats et attributs.

1.4 Méthodes

1.4.1. SITE À L'ÉTUDE

L'étude porte sur le territoire environnant le village de Kangiqsualujjuaq (Rivière George, 58°42'39''N-65°59'43''W) dans le Québec nordique (Nunavik, Fig. 1.1). Cette communauté est établie sur la rive de la baie Akilasakallak, environ 25 km en amont de l'embouchure de la rivière George. Selon les données climatiques de la station météorologique la plus proche, située à Kuujjuaq *ca* 160 km au sud-est, la temperature annuelle moyenne est d'environ -5,5 °C et les précipitations dépassent 500 mm (Environnement Canada, 2008). Le site se trouvant dans la zone de transition entre la toundra forestière et la toundra arbustive, il représente un secteur-clé pour l'étude des changements du couvert végétal en réponse au réchauffement climatique puisqu'on s'attend à ce que ces changements se produisent initialement dans les écotones entre les zones de végétation (Silapaswan et al., 2001). Le relief est formé d'une série de collines

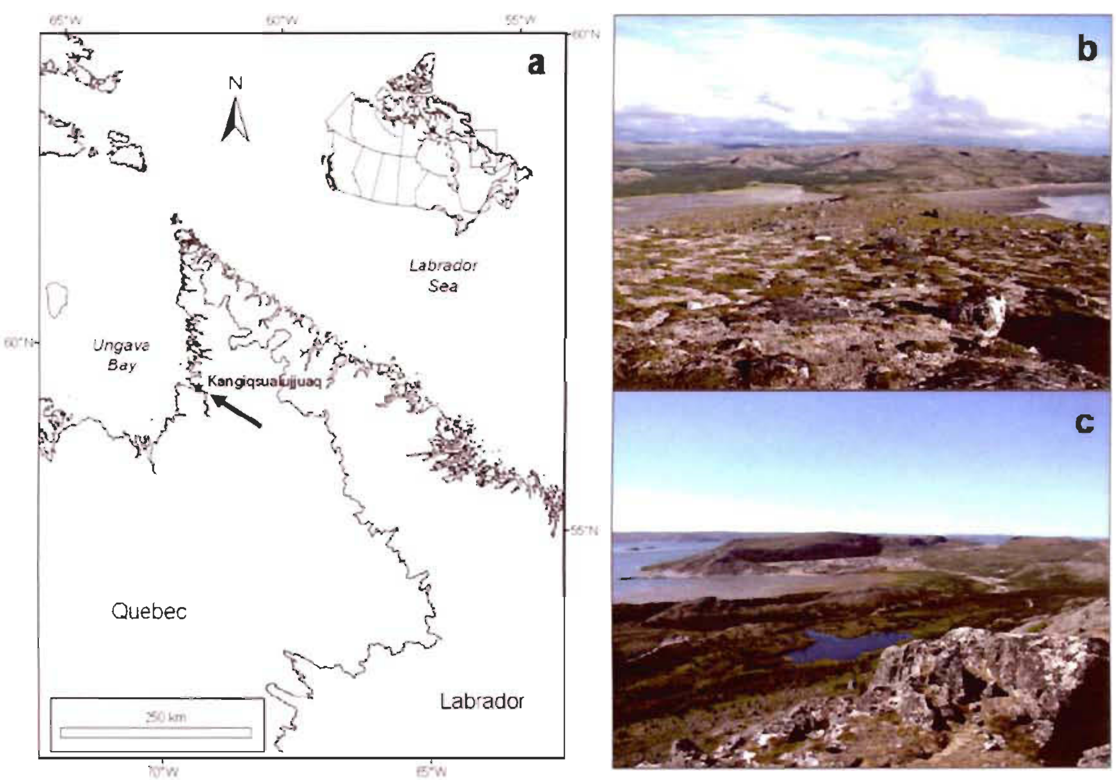

Figure 1.1. Localisation du site à l'étude, Kangiqsualujjuaq (Nunavik, Québec), sur la rive est de la baie d'Ungava (a) et vues générales du site à partir de plateaux sommitaux environnants le village (b, c) illustrant le relief, la végétation et le village situé en bordure de la baie Akilasakallak (c, arrière-plan).

ondulantes n'excédant pas 300 m d'altitude, à versants généralement abrupts et à sommets plats. Le substratum rocheux est constitué de gneiss archéen (Paradis et Parent, 2002). La végétation varie en fonction de l'altitude, passant de boréale-subarctique dans les basses terres protégées, à arctique dans les moitiés supérieures des versants et sur les plateaux sommitaux. De petites étendues de forêts composées d'épinette noire et de mélèze laricin (*Larix laricina* (Du Roi) K. Koch) occupent le fond des vallées et les portions inférieures des versants protégés.

1.4.2. ANALYSE DU COUVERT LIGNEUX ÉRIGÉ

1.4.2.1 Analyse des photographies aériennes verticales

L'analyse comparative du couvert ligneux érigé a été menée sur deux séries de photographies aériennes verticales monochromes couvrant les zones environnant le village de Kangiqsualujjuaq sur un rayon de 5-6 km. Les photos ayant servi de base pour la comparaison dataient de 1964 et leur échelle était de 1 : 15000 ou de 1 : 20000. Des orthophotographies à 0,5 m de résolution ont été générées à partir des versions papier issues de la Photothèque nationale de l'air (Ressources naturelles Canada). Les photos récentes dataient de 2003 et leur échelle était de 1 : 10000. Des orthophotos à 0,25 m de résolution ont été obtenues de la Géoboutique Québec (Ressources naturelles et Faune Québec). L'aire disponible pour l'analyse, constituée des surfaces terrestres non perturbées par l'homme et représentées conjointement par les deux séries de photos, était de 13,2 km^2.

L'analyse comparative des photos aériennes a été réalisée avec le logiciel ArcGIS (version 9.2 de ESRI). Le contour des surfaces couvertes de végétation ligneuse érigée (arbustes érigés et arbres), discernables par leur ton plus foncé et leur texture distincte, a été tracé sur les orthophotos de chaque année, les délimitant ainsi à l'intérieur de polygones. L'aire minimale pour que ces surfaces soient considérées a été fixée à 100 m^2 et leur contour a été tracé de façon à ce qu'elles soient incluses dans le plus petit polygone possible. Ces surfaces ont été classées en deux types de végétation selon les patrons de couvert observés. Celles qui présentaient un couvert de 90 % ou plus ont été classées comme étant à couvert continu. Ces surfaces se présentaient sous forme d'arbustaies et/ou d'arboraies denses et « fermées » où il y avait peu ou pas de place pour une augmentation du couvert ligneux érigé. Les surfaces où le couvert était compris entre 10 et 90 % ont été classées comme étant à couvert discontinu, soit des arbustaies et/ou des arboraies plus ou moins ouvertes formées d'individus isolés ou en agrégats occupant l'espace de façon hétérogène. Les limites de cette classe ont été fixées dans le but de couvrir un large intervalle de recouvrement; d'un part en raison de la difficulté à évaluer le couvert au sein de polygones à formes complexes, souvent étendus et dont le couvert variait beaucoup spatialement et, d'autre part, vu la complexité à délimiter les surfaces en utilisant des classes de recouvrement plus fines. Toutefois, un sous-échantillon de 100 polygones à couvert discontinu a été retenu pour chaque année afin d'évaluer le couvert moyen de cette classe. L'évaluation a été faite au sein d'un quadrat de 40 m de côté (1600 m^2) placé aléatoirement dans chaque polygone. Une valeur de couvert a été attribuée à chaque quadrat selon quatre sous-classes couvrant l'intervalle de la classe « couvert discontinu »: 10-30 %, 30-50 %, 50-70 % et 70-90 %. Enfin, le contour des surfaces dont le couvert ligneux érigé était inférieur à 10 % n'a pas été tracé et elles ont été considérées au même titre que les surfaces dépourvues d'une telle végétation. Ces surfaces à couvert inférieur à 10 % ne présentaient que des individus sporadiques et très isolés dont l'influence sur le milieu en général apparaissait négligeable.

L'augmentation nette du couvert ligneux érigé a été calculée en comparant la somme des surfaces de l'ensemble des polygones de 1964 et de 2003. Les surfaces nouvellement colonisée de façon discontinue et continue en 2003 a été calculée de la même façon mais en soustrayant d'abord à la surface totale de chaque type la surface des endroits où le couvert s'est refermé, c'est-à-dire là où la classification est passée de discontinue en 1964 à continue en 2003.

Trois paramètres environnementaux ont été utilisés pour préciser les types de milieu où ces changements ont eu lieu : l'altitude, la pente et l'exposition. Des cartes de pente et d'exposition ont été générées à partir d'un modèle numérique d'élévation (MNE) à 2 m de résolution. Quatre classes ont été déterminées pour chaque paramètre.

Les 4 points cardinaux ont servi de valeurs médianes pour les 4 classes d'exposition (90 ° chacune). Les limites des classes d'altitude et de pente ont été établies en fonction de la distribution des fréquences générées à l'aide d'ArcGIS et selon leur signification écologique (*cf.* Table 2.2, Chapitre 2).

La surface analysée sur les deux séries de photos aériennes est de 720 hectares, soit plus de la moitié (55 %) des 13,2 km^2 disponibles pour l'analyse. Les surfaces analysées sont distribuées sur l'ensemble du territoire à l'étude et représentent au moins 30 % de la surface totale de chaque classe de paramètres environnementaux.

1.4.2.2 Validation sur le terrain

Les polygones délimitant le couvert ligneux érigé en 1964 et en 2003 ont été superposés et fusionnés afin d'extraire ceux où ce couvert a augmenté. Trois types de polygones ont été obtenus : ceux où le couvert s'est refermé, passant de discontinu en 1964 à continu en 2003 (1) et ceux où il y a eu une nouvelle colonisation, soit les surfaces dépourvues d'arbustes érigés ou d'arbres en 1964 mais présentant un couvert discontinu (2) ou continu (3) en 2003. Des valeurs moyennes d'altitude, de pente et d'exposition ont été attribuées à chacun de ces polygones qui ont par la suite été placés dans l'une ou l'autre des classes de ces trois paramètres environnementaux. Un échantillonnage aléatoire stratifié, basé sur les combinaisons de classes de paramètres environnementaux et de types de polygones (fermeture du couvert, nouveau couvert discontinu et continu) a permis de sélectionner les polygones qui serviraient pour la validation sur le terrain. Les centroïdes des polygones retenus ont été générés avec ArcGIS et leurs coordonnées géographiques ont servi de position sur le terrain pour les parcelles de validation. Les parcelles étaient circulaires et d'un diamètre de 10 m. Chacune a été décrite (type d'habitat, drainage, substrat, perturbations naturelles et anthropiques). La hauteur, le pourcentage de recouvrement et la présence de semis et/ou de gaulis ont été déterminés pour chaque espèce ligneuse érigée présente dans les parcelles. Afin d'obtenir des données sur les sites qui n'avaient toujours pas été colonisés par des arbustes érigés ou des arbres en 2003, dix parcelles supplémentaires ont été positionnées de façon aléatoire dans des endroits apparemment dépourvus de ce type de végétation sur les orthophotos de 1964 et de 2003. La validation sur le terrain a été effectuée du 17 juillet au 2 septembre 2008.

1.4.3 DENDROCHRONOLOGIE EXPLORATOIRE

Lors de l'analyse comparative des orthophotos, plusieurs arbres ont été observés sur les photos de 2003 qui étaient absents sur celles de 1964. Au-delà de 1200 nouveaux arbres ont été recensés durant l'analyse et leurs coordonnées géographiques ont été générées avec ArcGIS afin de pouvoir les retrouver une fois sur le terrain. Dans un but exploratoire, 10 de ces arbres ont été sélectionnés de façon aléatoire et récoltés afin d'en déterminer l'âge et d'en étudier les cernes de croissance. Les 10 arbres ont été récoltés dans trois types d'habitat : trois dans une basse terre côtière, quatre sur un sommet exposé et xérique de colline rocheuse ainsi que dans le talus de blocs sous-jacent et trois dans une mi-pente mésique exposée au sud. De plus, trois gaulis sélectionnés sur place ont été récoltés sur la colline rocheuse. Les mesures des cernes de croissance ont été effectuées au Centre d'études nordiques (Université Laval) avec une table micrométrique Velmex (précision 2 μm) le long de deux rayons opposés tracés de façon aléatoire mais évitant le bois de réaction.

1.5 Résultats

1.5.1 ANALYSE DU COUVERT LIGNEUX ÉRIGÉ

Au cours des 40 ans séparant les deux séries de photos aériennes, le couvert ligneux érigé s'est étendu de façon substantielle. Près de 16 % des surfaces qui étaient dépourvues ou presque d'arbustes érigés ou d'arbres en 1964 (couvert <10 %) ont été colonisées par ceux-ci à divers degrés. La majorité de ces surfaces sont de type discontinu et leur couvert moyen était de 37 % en 2003. Si on considère 5 % comme couvert moyen de ces mêmes surfaces en 1964 (valeur médiane de <10 %), on obtient une augmentation moyenne de 32 % du couvert ligneux érigé en 40 ans. Plus d'un tiers du couvert discontinu en 1964 (7,4 % de la surface totale analysée) a été l'objet d'une fermeture suffisante pour passer à un couvert continu en 2003. Leur couvert moyen est passé de 59 % en 1964 à 95 % (valeur médiane de l'intervalle de classe du couvert continu) en 2003, une hausse de 36 %. Les surfaces à couvert discontinu en 1964 qui le sont demeurées en 2003 (13 % de la surface totale analysée) ont elles aussi été l'objet d'une fermeture du couvert, de l'ordre de 15 % (couvert moyen de 47 % en 1964 et de 62 % en 2003). Au total, c'est donc plus de 36 % de l'aire analysée qui a subi une augmentation claire du couvert ligneux érigé entre 1964 et 2003. Cette proportion atteint 55 % si on considère uniquement les surfaces disponibles à la colonisation ou à une fermeture du couvert à partir de 1964, c'est-à-dire si on exclut du calcul celles qui avaient déjà un couvert continu en 1964.

Bien que le couvert ligneux érigé ait augmenté dans toutes les classes de paramètres environnementaux, l'ampleur du changement varie d'une classe à l'autre. Il y a eu une plus grande augmentation relative dans les classes de plus haute élévation (>70 m) de même que sur les terrains plats et les pentes faiblement inclinées. Enfin, l'augmentation relative est légèrement supérieure dans les sites exposés au sud et à l'est.

1.5.2 VALIDATION SUR LE TERRAIN

Les travaux de validation sur le terrain ont consisté en 345 parcelles distribuées dans les sites où le couvert ligneux érigé a augmenté. Celles-ci se subdivisent en 158 parcelles dans le nouveau couvert discontinu, 75 dans le nouveau couvert continu et 112 dans les sites où le couvert s'est refermé. Dix parcelles supplémentaires ont été réalisées dans des milieux qui étaient toujours dépourvus de végétation ligneuse érigé sur les photos de 2003.

Dans le site à l'étude, les travaux de validation démontrent clairement que le bouleau glanduleux est l'espèce la plus fréquente et la plus abondante là où le couvert ligneux érigé a augmenté. Cette espèce domine le couvert ligneux érigé dans 85 % des 345 parcelles et elle est présente dans 98 % de celles-ci. Le couvert ligneux érigé est composé uniquement de bouleau glanduleux dans 75 parcelles. Le saule à feuilles planes (*Salix planifolia* Pursh), le saule glauque (*Salix glauca* L. var. *callicarpaea* (Trautv.) Argus), le mélèze laricin et le thé du Labrador (*Rhododendron groenlandicum* (Oeder)

Kron & Judd) étaient également fréquents dans les parcelles, bien qu'ils en dominaient rarement le couvert.

Les valeurs de recouvrement illustrent bien l'abondance du bouleau glanduleux là où le couvert ligneux érigé a augmenté. Le couvert moyen de cette espèce était de 48 % dans l'ensemble des parcelles où elle était présente, et de 52 % dans celles où elle dominait le couvert. Dominante ou non, cette espèce était donc globalement abondante, ce qui n'était pas le cas pour les autres espèces. Bien que leur couvert moyen pouvait être élevé (entre 22 % et 70 %) dans les rares parcelles où elles étaient dominantes, il était faible (entre 2 % et 23 %) dans l'ensemble des parcelles où elles étaient présentes.

Dans les sites où le couvert ligneux érigé s'est accru, l'importance du bouleau glanduleux est également attestée par la fréquence relativement élevée de semis de cette espèce (Fig. 1.2 a), qu'on trouvait dans 37 % des parcelles de validation. Ces semis occupaient principalement les micro-sites perturbés, surtout sur sol minéral à nu associé aux ostioles de toundra. Les semis de thé du Labrador étaient également fréquents et ont été trouvés dans plus de 12 % des parcelles. Dans l'ensemble, plus de 41 % des parcelles de validation contenaient des semis d'arbustes érigés. Une découverte inattendue a été l'abondance de semis et de gaulis de mélèze laricin (Fig. 1.2 b) principalement en-deçà de 70 m d'altitude, dans les versants au-dessus de la ligne des arbres (Fig. 1.3) ainsi que dans les milieux ouverts des basses terres tels que le sommet des palses minérales ou organiques. Un quart des parcelles contenait des semis et/ou des gaulis de cette espèce, leur densité pouvant dépasser 1/m² dans certaines parcelles.

Moins du tiers (29 %) des surfaces analysées n'étaient pas colonisées par des arbustes érigés ou des arbres sur les photos de 2003. Les 10 parcelles positionnées de façon aléatoire dans ces milieux ont révélé que ces surfaces étaient 1) des champs de blocs, 2) des affleurements rocheux, 3) des plateaux sommitaux exposés avec blocs et substrat minéral à nu en abondance et 4) des fens à cypéracées occupant surtout le fond des vallées et l'aval des terraces de nivation le long des versants. La majorité des surfaces non colonisées étaient représentées par ces deux derniers types d'habitats.

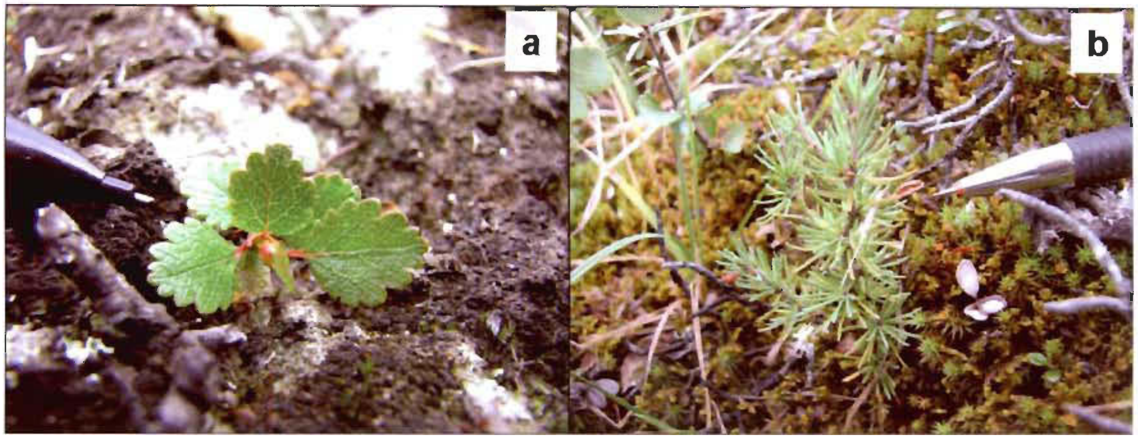

Figure 1.2. Semis de bouleau glanduleux (*Betula glandulosa*) (a) et de mélèze laricin (*Larix laricina*) (b), environs de Kangiqsualujjuaq (Nunavik, Québec).

Figure 1.3. Vue vers le sud d'un versant situé au nord-est de Kangiqsualujjuaq, montrant de nombreux gaulis de mélèze laricin récemment établis au-delà de la ligne des arbres, ce qui suggère que ceux-ci ont entamé une migration vers le haut des versants.

1.5.3 DENDROCHRONOLOGIE EXPLORATOIRE

Tous les arbres récoltés se sont avérés être des mélèzes laricins. Conséquemment, des gaulis de la même espèce ont été prélevés. Les 10 arbres étaient âgés entre 49 et 69 ans alors que les 3 gaulis avaient entre 14 et 27 ans. L'analyse des cernes de croissance a révélé un patron similaire chez l'ensemble des arbres, soit des cernes relativement étroits durant les premiers 30 à 50 ans après l'établissement, suivis d'une augmentation marquée de la largeur des cernes à partir de *ca* 1990; les cernes les plus larges étant observés durant la dernière décennie. Dans le cas des gaulis, la largeur des cernes de croissance augmente de façon graduelle et continue à partir du moment de l'établissement et l'un des gaulis montre des cernes initiaux déjà relativement larges.

1.6 Conclusions

Dans l'ensemble, l'analyse comparative de photographies aériennes verticales anciennes et récentes a permis de détecter une augmentation substantielle du couvert ligneux érigé dans les environs de Kangiqsualujjuaq (Nunavik, Québec) pour la période comprise entre 1964 et 2003. Au cours des 40 ans séparant les deux séries de photos, un estimé minimal de 55 % des surfaces disponibles ont été soit colonisées par des arbustes érigés et/ou par des arbres, soit l'objet d'une fermeture partielle ou totale du couvert préexistant. Cette augmentation est attribuable en majorité au bouleau glanduleux et pourrait avoir été causée par l'effet combiné de températures récentes plus chaudes et de l'ouverture du couvert lichénique par le broutement et le piétinement des caribous. Dans le cas du mélèze laricin cependant, il semble que de meilleures conditions climatiques représentent le facteur prépondérant à l'origine de l'abondance des jeunes recrues et conséquemment de la hausse de la limite altitudinale des arbres. Bien que la surface étudiée soit limitée d'un point de vue global, l'analyse d'images satellites à l'échelle régionale pour la période 1988-2002 (W. Chen et al., soumis) concorde avec nos résultats. On pouvait s'attendre à ce que la tendance générale au réchauffement du climat depuis la fin du Petit Âge Glaciaire soit associée à une certaine expansion du couvert ligneux érigé. Toutefois, l'ampleur de l'augmentation détectée dans le site à l'étude apparaît anormalement élevée pour une période aussi courte (40 ans) et suggère une accélération récente à la fois dans l'évolution du couvert végétal vers une toundra davantage occupée par des arbustes érigés et dans sa colonisation locale par des arbres près de la limite méridionale de l'Arctique. Cette observation est appuyée par le savoir écologique local, les données de température, l'analyse des cernes de croissance de mélèzes laricins et l'abondance des jeunes recrues de cette espèce, de même que par les photographies obliques répétées avec un intervalle de 20 ans entre les photos anciennes et récentes. Il est probable qu'une augmentation similaire du couvert ligneux érigé ait eu lieu ailleurs dans l'est de l'Arctique canadien dans des sites de latitude et de conditions environnementales comparables. Cette hypothèse doit cependant être davantage appuyée par la réalisation d'études à fine échelle d'autres localités de l'est de l'Arctique canadien, en association avec l'analyse d'images satellites.

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CHAPITRE II

RECENT EXPANSION OF ERECT WOODY VEGETATION IN THE CANADIAN EASTERN LOW ARCTIC

Benoît Tremblay, Esther Lévesque et Stéphane Boudreau

Le manuscrit sera soumis pour publication
dans la revue *Arctic, Antarctic and Alpine Research*

2.1 Résumé

Nous avons fait une analyse comparative de deux séries (1964 et 2003) de photographies aériennes verticales des environs de Kangiqsualujjuaq (Nunavik, Québec) afin de déterminer si le couvert ligneux érigé de ce secteur a augmenté récemment en réponse au réchauffement du climat. Durant la période de 40 ans séparant les deux séries de photos, plus de la moitié des surfaces disponibles a été l'objet d'une colonisation ou d'une fermeture du couvert par des arbustes érigés et/ou par des arbres. L'augmentation relative du couvert ligneux érigé a été supérieure à plus haute altitude et sur les pentes de plus forte inclinaison, de même que sur les sites exposés au sud et à l'ouest. Le bouleau glanduleux (*Betula glandulosa* Michx.), une espèce d'arbuste érigé, est essentiellement responsable de cette augmentation. Des semis et des gaulis de mélèze laricin (*Larix laricina* (Du Roi) K. Koch) ont été trouvés en abondance le long des versants au-delà des zones antérieurement boisées, suggérant d'une part que cette espèce pourrait jouer à court terme un rôle plus important dans l'augmentation du couvert ligneux érigé et, d'autre part, qu'un processus de migration de la limite altitudinale des arbres vers le haut des versants est entamé. Les sites qui n'avaient toujours pas été colonisés par des arbustes érigés ou par des arbres sur les photos de 2003 sont ceux où 1) l'établissement est impossible en raison de l'absence de substrat meuble et 2) l'établissement et la croissance sont grandement restreints par le couvert végétal préexistant ou par des conditions environnementales sévères persistantes. Les résultats de cette étude concordent avec ceux issus de l'analyse d'images satellites à l'échelle régionale pour la période 1988-2002.

2.2 Abstract

We conducted a comparative analysis of two series (1964 and 2003) of vertical aerial photos from the vicinity of Kangiqsualujjuaq (Nunavik, Quebec) to determine if this area was affected by an increase in erect woody vegetation in response to recent warming. During the 40 years spanning the two photo series, more than half of available surfaces were affected by new colonization or infilling by erect shrubs and/or trees. Relative increase is greater on steeper slopes and at higher altitudes, as well as on sites of southern and eastern exposure. *Betula glandulosa* Michx. (dwarf birch) is essentially responsible for this increase. Seedlings and saplings of *Larix laricina* (Du Roi) K. Koch (eastern larch) were found in abundance on hillsides above pre-existing woodlands, suggesting both that this species may locally play a greater role in erect woody vegetation increase in the near future and that altitudinal tree line is migrating upslope. Sites still uncolonized by erect shrubs or trees in 2003 are ones where 1) establishment is not possible due to absence of loose soil and 2) establishment and growth are greatly hindered by pre-established vegetation cover or ongoing severe local environmental conditions. Results are consistent with regional-scale satellite image analysis of the study area for the period 1988-2002.

2.3 Introduction

A major functional response of arctic terrestrial ecosystems to warming is land cover change (Levis et al., 1999; Kittel et al., 2000; Beringer et al., 2005) and erect shrubs (≥0,5 m) are among the vegetation types that respond the most (Bret-Harte et al., 2002). Increasing shrub cover has profound consequences on many ecological factors, such as decreased albedo and heightened sensible heat flux to the atmosphere and ground (Sturm et al., 2005a) as well as greater snow accumulation, active layer depth and summer evapotranspiration (Sturm et al., 2001a; Pomeroy et al., 2006; Strack et al., 2007). Furthermore, chemical equilibrium and soil nutrient cycling are altered through changes in production and accumulation of woody material (carbon sequestration), through higher amounts of organic debris retained during transit (Fahnestock et al., 2000) and through warmer soil winter temperatures. The latter enhance decomposition (Grogan and Chapin, 2000; Schimel et al., 2004; Sturm et al., 2005b), which in turn may promote spring and summer growth. Gaining proper knowledge of actual land cover change therefore appears critical to comprehend how the Arctic responds to climate change.

In experimental warming studies using open-top chambers (OTCs) erect shrubs have responded, in some cases dramatically, by increased growth and canopy closure of pre-established individuals (Chapin et al., 1995; Chapin and Shaver, 1996; Hobbie and Chapin, 1998; Bret-Harte et al., 2001, 2002; Van Wijk et al., 2003; Jonsdottir et al., 2005; Wahren et al., 2005; Walker et al., 2006), with corresponding detrimental effects on non vascular elements of the vegetation cover (Walker et al., 2006).

Most indications of shrub expansion in the Arctic are anecdotal. To our knowledge, the only study to provide actual data on the extent and species responsible is that of Tape et al. (2006), who documented a substantial erect shrub expansion in the past 50 years over 320 km^2 of arctic landscape in Alaska. Indirect evidence of shrub cover increase is provided through comparative analysis of satellite images which show a steady increase of Normalized Difference Vegetation Index (NDVI) in northern latitudes of North America for at least the past 20 years (Myneni et al., 1997; Goetz et al., 2005). In tundra ecosystems, increased NDVI values are closely related to shrub abundance (Jia et al., 2004). The expansion of shrubs is also suggested by local tree line advances, which have been detected in Quebec (Gamache and Payette 2004, 2005), Manitoba (Scott et al., 1987; Scott and Hansell, 2002), Alaska (Cooper, 1986; Rowland, 1996; Suarez et al., 1999; Lloyd et al., 2002; Lloyd and Fastie, 2003) and Russia (Shvartsman et al., 1999). As these advances appear to be the result of warmer climatic conditions (Hinzman et al., 2005), shrub elements of the vegetation cover are also expected to respond positively in these areas. Furthermore, growth ring analysis of *Salix lanata* L. *s. lat.* (woolly willow) from the Russian Arctic shows increased growth for the period 1942-2005 (Forbes et al., in press), a find supported by local ecological knowledge and consistent with NDVI analysis. This growth increase may have translated in an expansion of its cover in this region.

The nature and extent of shrub cover increase remains unknown for most of the Arctic, and the Canadian Eastern Arctic is no exception. With this paper, we provide evidence of substantial erect shrub and low tree expansion in the north-eastern Quebec Low-Arctic over the past 40 years, through comparative analysis of past (1964) and current (2003) vertical aerial photos of areas surrounding the village of Kangiqsualujjuaq.

2.4 Methods

2.4.1 STUDY SITE

The study was undertaken around the community of Kangiqsualujjuaq (George River, 58°42'39''N-65°59'43''W) in northern Quebec (Nunavik, Fig. 2.1). This community is located on the south-east side of Ungava Bay, *ca.* 25 km upstream from the mouth of the George River, on its east side along the shores of Akilasakallak Bay. Being located in the forest – shrub tundra transition zone, the study site represents a key area as initial changes in vegetation are expected to happen in ecotones between vegetation zones (Silapaswan et al., 2001). Long-term climatic data (1948-2008) from the nearest available meteorological station at Kuujjuaq (160 km to the south-west) indicate a mean annual temperature of about -5,5°C and mean annual precipitations that exceed 500 mm (Environment Canada, 2008).

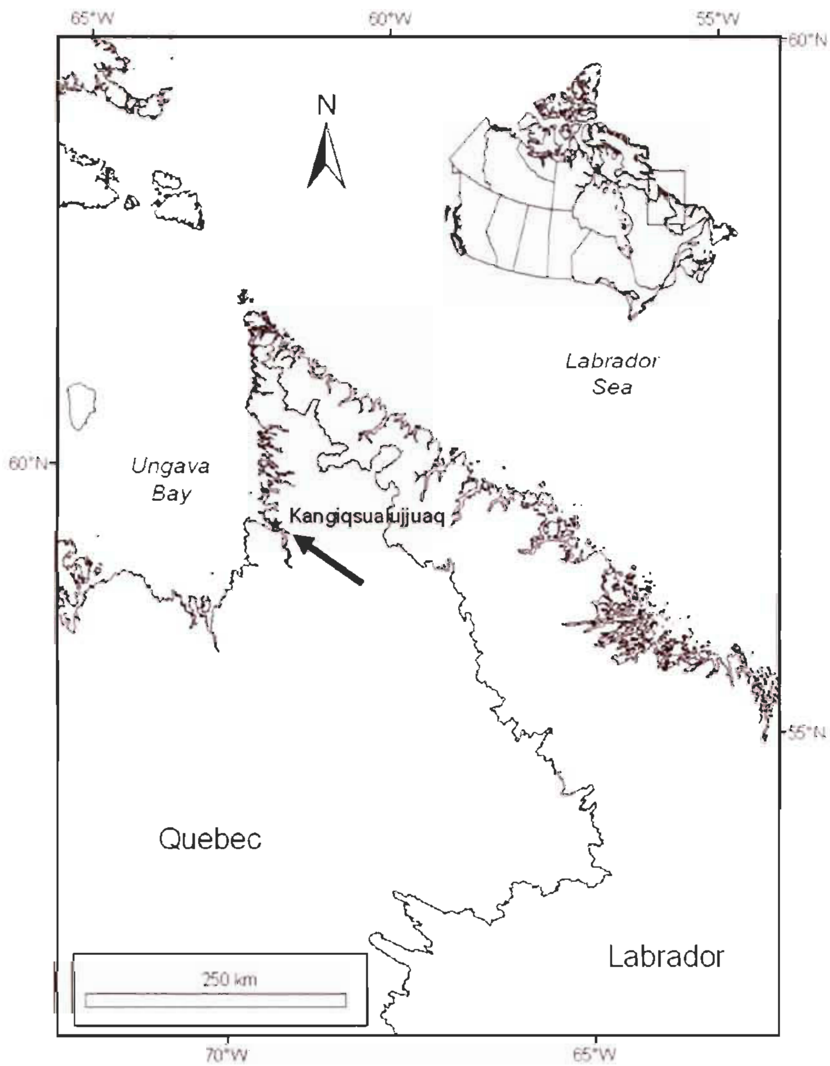

Figure 2.1. The study site, Kangiqsualujjuaq (Quebec, Canada), near the southeastern shore of Ungava Bay.

General topography is a series of usually steep sided flat-topped hills that do not exceed 300 m altitude, mainly 200 m or less. Bedrock is archean gneiss, with some quartzites and amphibolites (Paradis and Parent, 2002). Vegetation varies greatly with altitude, grading from boreal-subarctic on protected lowlands to arctic on mid slopes and hilltop plateaus (Table 2.1). Small expanses of closed-crown coniferous forests are still

Table 2.1. Physical characteristics and associated vegetation of the study site, Kangiqsualujjuaq (Nunavik, Quebec), as determined from field observations. Taxa nomenclature follows either Flora of North America treatment when present in published volumes, or various recent taxonomy papers otherwise

Topographical divisions	Substrate	Periglacial forms	Vegetation	Main species
Lower slopes, valley floors and coastal areas	Alluvial and/or peat deposits covering marine sediments; reworked till higher up; bare rock along the river and on exposed headlands	Thufa; palsas and thermokarst ponds on the east side of Akilasakallak Bay	Coniferous forests	*Picea mariana* (Mill.) BSP, *Larix laricina* (Du Roi) K. Koch (to 20 m high); *Pleurozium shreberi* (Willd.) Mitt. or *Sphagnum* spp. on forest floors
			High shrub thickets	*Salix planifolia* Pursh (to 3 m high); some *Salix argyrocarpa* Anderss., *Salix glauca* L. var. *callicarpaea* (Trautv.) Argus and *Betula glandulosa* Michx.
			Sedge fens and bogs	*Carex rariflora* (Wahlenb.) Sm., *Eriophorum angustifolium* Honck. subsp. *angustifolium*, *E. vaginatum* L.; *Sphagnum* spp., minerotrophic mosses
Mid slopes	Reworked till, boulder fields and talus, rock outcrops, peat deposits on nivation terraces	Nivation hollows and terraces, solifluction soil	Open larch woodland	*Larix laricina* (8-15 m high), *Picea mariana* krummholzs, *Betula glandulosa*; *Cladina* spp.
			Low erect shrub tundra	*Betula glandulosa*, *Empetrum nigrum* L., *Rhododendron groenlandicum* (Oeder) Kron & Judd, *Rhododendron tomentosum* Harmaja, *Vaccinium uliginosum* L., *V. vitis- idaea* L., *Arctous alpina* (L.) Nied.
			Alder thickets (on south exposed slopes along the river)	*Alnus viridis* (Chaix) DC. subsp. *crispa* (Ait.) Turrill (to 2 m high)
			Sedge fens (on nivation terraces)	Same as in lowlands
Steep upper slopes, cliffs and hilltop plateaus	Till, rock outcrops, boulder fields	Tundra ostioles, solifluction soils, ill structured polygon soils	Short windswept *Betula* thickets	*Betula glandulosa*, *Rhododendron tomentosum*, *Empetrum nigrum*; *Picea mariana* krummholzs; *Cladina* spp.
			Lichen, moss, prostrate dwarf shrub tundra	*Cladina* spp., *Flavocetraria* spp.; *Racomitrium lanuginosum* (Hedw.) Brid.; *Arctous alpina*, *Diapensia lapponica* L., *Vaccinium vitis-idaea*, *Kalmia procumbens* (L.) Gift & Kron, *Anthoxanthum monticolum* (Bigel.) Veldkamp subsp. *alpinum* (Sw.) Soreng, *Oxytropis campestris* (L.) DC. subsp. *johannensis* (Fern.) Blondeau & Gervais

present on valley bottoms and lower parts of hillsides, where trees as high as 20 m may be found. Moving upslope, tree density and height diminish progressively. Local tree line is at 80 m a.s.l., but on some well protected and favourably exposed valley sides, it may attain 150 m.

2.4.2 ERECT WOODY VEGETATION CHANGE ANALYSIS

2.4.2.1 Aerial vertical photograph analysis

Comparative analysis was conducted on two series of vertical aerial photographs spanning the community of Kangiqsualujjuaq and surrounding areas over a *ca* 5-6 km radius. The first series of aerial photographs dated back to August 6^{th} 1964. Monochrome contact prints at 1: 15 000 and 20 000 scales were obtained from the National Air Photo Library of Natural Resources Canada. Digital orthorectified and georeferenced files of these prints were created at a 0.5 m resolution. The recent aerial photographs were taken July 24^{th} 2003 and are at a 1: 10 000 scale. Monochrome orthophotographs at a 0.25 m resolution of these 2003 photos were obtained from the Géoboutique Québec (Ressources naturelles et Faune Québec). Total area of overlap of the two photo series is 17 km^2, of which 14.3 km^2 is land surface. However, only 13.2 km^2 were undisturbed by human activities and available for analysis.

Shrub covered areas on the photographs can be detected by their darker shade and distinct texture created by the foliage and the roundish aspect of each shrub seen from above (Fig. 2.2). Trees are easily detected by the triangular shape of their projected shade. Furthermore, the surrounding environment was taken into consideration during analysis, which brought precisions on general habitat and provided clues on the possible nature of the vegetation cover observed.

During analysis with ArcGIS (version 9.2 from ESRI), we used a stretched symbology with standard deviations as stretch type ("n" values between 1.5 and 2.5) for orthophoto display. Contours of surfaces covered by erect woody vegetation were traced, delimiting them inside polygons. Minimum area for these surfaces to be

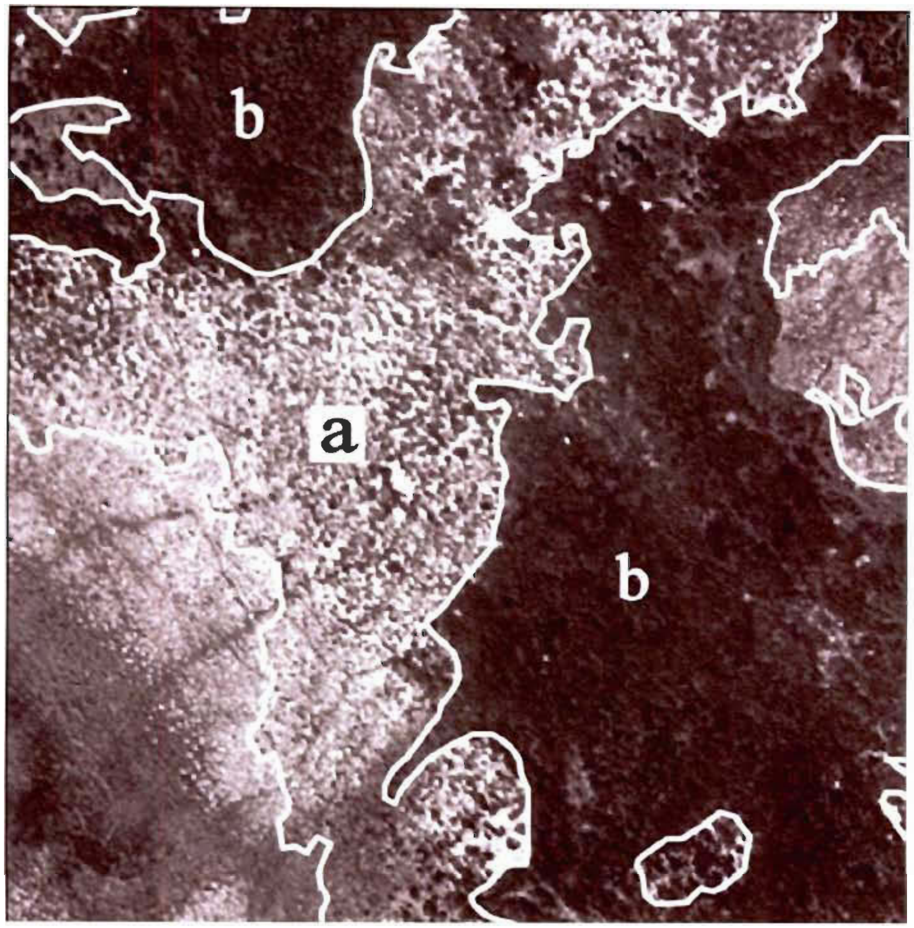

Figure 2.2. Part of a 2003 orthophotograph showing examples of a) discontinuous and b) continuous erect shrub cover. Darker shade of erect shrubs is easily seen in both vegetation types, but distinct texture is most evident in the continuous cover polygons. Source of background image: orthophotograph 24i12-1702, © Quebec Government, Ministry of Natural Resources and Wildlife.

considered was fixed at 100 m^2 and contours were traced in order to encompass them in the smallest possible polygons. Analysis was thus kept at the smallest scale above the minimum area, enclosing less possible non shrub/tree covered land inside the polygons. With this method, analysis was generally made at a view scale between 1: 400 and 1: 800. Surfaces covered by erect woody vegetation were classified in two vegetation types according to observed cover patterns. Those with 90 % cover or more were classified as "continuous cover". They presented closed canopy shrubland and/or woodland with essentially no possibility of total cover increase (Fig. 2.2). Surfaces with cover between 10 % and 90 % were classified as "discontinuous cover", displayed on the photos as patchy shrubs or shrub thickets and isolated or aggregated trees, all with a heterogeneous spatial distribution (Fig. 2.2). Limits of this class were fixed in such a way as to include a large cover interval, for two reasons: 1) the difficulty to evaluate cover inside polygons that were frequently extensive, with irregular contours and showing spatially variable cover and 2) the complexity of polygon delineation using finer cover classes. Nonetheless, to evaluate mean cover of this class, 100 discontinuous cover polygons were randomly retained for each year. Evaluation was made in a 40 X 40 m (1600 m^2) quadrat randomly placed inside each polygon and using four narrower cover classes spanning the whole interval of the discontinuous cover class: 10-30 %, 30-50 %, 50-70 % and 70-90 %. Surfaces with some erect woody vegetation but below 10 % cover contained only very isolated individuals with an apparently negligible influence on general habitat. These surfaces were not delineated and included with those devoid of erect woody vegetation.

Net increase of surfaces covered by erect woody vegetation (discontinuous and continuous) was calculated by taking the percent of land surface analyzed covered by this vegetation in 2003 to which was subtracted the same surface for 1964. Some surfaces where erect woody vegetation was classified as discontinuous in 1964 underwent sufficient infilling to be classified as continuous in 2003. Total area of these infilled surfaces was subtracted to both 1964 discontinuous and 2003 continuous cover to determine newly colonized surfaces (from <10 % in 1964 to either 10-90 % (discontinuous) or >90 % (continuous) in 2003), which were calculated as follows:

Discontinuous cover:

$$\frac{03D \times 100}{TS} - \frac{(64D - DC) \times 100}{TS}$$

Continuous cover:

$$\frac{(03C - DC) \times 100}{TS} - \frac{64C \times 100}{TS}$$

Where:

TS: total land surface analyzed

DC: surface of 1964 discontinuous erect woody vegetation cover that has shifted to continuous in 2003;

64D: 1964 surface of discontinuous erect woody vegetation;

64C: 1964 surface of continuous erect woody vegetation;

03D: 2003 surface of discontinuous erect woody vegetation;

03C: 2003 surface of continuous erect woody vegetation.

In order to specify in which landscape types detected changes in erect woody vegetation were located, three environmental parameters were used: altitude, slope and exposure. A digital elevation model (DEM) at a 2 m resolution was generated using the vectorial data of the 1: 50 000 maps of the area (24I12, 24I13, 24J09, 24J16). This DEM was used to generate raster datasets of slope and exposure with ArcGIS. Four classes were created for each environmental parameter. The 4 cardinal points were used as middle point of exposure classes (90° each). In the case of altitude and slope, boundaries of the classes were fixed based on the natural breaks of the distribution of values as plotted with ArcGIS, and on their ecological significance (Table 2.2). Raster datasets of these parameters, classified as shown in Table 2.2, were created for total area occupied respectively by the 1964 and 2003 polygons, and for total polygons of each vegetation cover type (continuous (1) and discontinuous (2) for both years, 1964 discontinuous changed to continuous in 2003 (3)). The sum of pixels in each class of parameters was multiplied by pixel surface (4 m^2) to obtain net surface occupied by erect woody vegetation and vegetation cover type in each class. The equations presented above were used to calculate net increase in each environmental parameter class.

Erect woody vegetation cover of the two photo series was analyzed on 720 hectares of land surface essentially undisturbed by human activity, which represents more than half (55 %) of the 13.2 km^2 available for comparative analysis (Table 2.3). Analyzed surfaces are distributed over the entire study area and represent at least 30 % of total surfaces of each environmental parameter class.

Table 2.2. Classes of environmental parameters as determined for the purpose of this study

Environmental parameter	**Class**	**Description**
Altitude (m)	0-20	Coastal areas
	20-70	Valley bottoms and lower part of slopes
	70-120	Mid to upper slopes
	>120	Upper slopes and hilltop plateaus
Slope (°)	0-5	Flatland to lowly inclined slopes
	5-15	Medium slopes
	15-30	Steep slopes
	>30	Very steep slopes and cliffs
Exposure	N	Northwest to northeast (315-360° & 0-45°)
	E	Northeast to southeast (45-135°)
	S	Southeast to southwest (135-225°)
	W	Southwest to northwest (225-315°)

2.4.2.2 Ground truthing

Photo analysis is subject to uncontrollable bias sources such as image quality and local shading linked to topography and clouds. Also, determination of tree and shrub species is not possible on aerial photos. For these reasons, ground truthing was necessary.

Polygons of each year, which delimit areas occupied by erect shrubs and/or trees, were superimposed and united to extract polygons where erect woody vegetation cover has increased. These polygons were of three types: from devoid of erect woody vegetation in 1964 to either discontinuous (1) or continuous (2) cover in 2003, or from discontinuous cover in 1964 to continuous cover in 2003 (3) through infilling. Mean values of altitude, slope and exposure were determined for each of these polygons, which were then attributed a class of altitude, slope and exposure depending on the mean value of each parameter within a given polygon. Combinations of increase types (new discontinuous or continuous cover, infilled) and environmental parameters were thus created for each polygon.

Table 2.3. Synthesis of study area surfaces and of area analyzed jointly on the 1964 and 2003 photo series in the vicinity of Kangiqsualujjuaq (Nunavik), by environmental parameter (altitude, slope and exposure) and in total

	Study area*		**Analyzed area**		
	Surface (ha)	Proportion of total study area (%)	Surface (ha)	Proportion of total analyzed area (%)	Proportion of study area class (%)
Altitude (m)					
0-20	140	10.6	111	15.4	79.3
20-70	485	36.7	361	50.1	74.4
70-120	333	25.2	123	17.1	36.9
>120	362	27.4	125	17.4	34.5
Slope (°)					
0-5	540	40.9	332	46.1	61.5
5-15	566	42.9	292	40.6	51.6
15-30	177	13.4	85	11.8	48.0
>30	35	2.7	11	1.5	31.4
Exposure					
North	311	23.6	105	14.6	33.8
South	447	33.9	306	42.5	68.5
East	181	13.7	82	11.4	45.3
West	381	28.9	227	31.5	59.6
TOTAL	**1320**	**100.0**	**720**	**100.0**	**54.5**

* Land area of overlap between the 1964 and 2003 photo series, excluding surfaces disturbed by human activity.

Selection of polygons for ground truthing was made by proportional stratified random sampling using the different combinations of vegetation cover types and environmental parameters. All polygons situated 20 m or less from disturbed areas were excluded from sampling. The centroid of each polygon retained was computed with ArcGIS and used as the field plot location. Each 10 m diameter ground truthing plot was described (general habitat, drainage, soil, natural and anthropogenic disturbance); height, percent cover and presence of seedlings, saplings and suckers was determined for each erect woody species and general as well as close-up photos were taken. Ten plots were randomly positioned inside areas seemingly devoid of shrub or tree cover on both the 1964 and 2003 orthophotos. The same data as described above were taken in these plots. Their purpose was to provide information on the habitats which had not been colonized by erect woody vegetation, and if such colonization could be expected in the near future. Furthermore, views of past ground photos from the vicinity of the village were retaken in 2008, as a qualitative means to show change in vegetation cover. Ground truthing took place during the summer of 2008, from July 17th to September 2nd.

2.4.3 EXPLORATORY DENDROCHRONOLOGY

During aerial vertical photo analysis, many trees were noticed on the 2003 photos that were absent on the 1964 ones. These "new" trees were mainly located on hillsides and openings in woodlands on the east side of Akilasakallak Bay. Over 1200 of these trees were inventoried during photo analysis and their geographical coordonates were generated to enable their location once in the field. For exploratory purposes, 10 trees were randomly selected and were harvested for age determination and growth ring analysis. These were collected in 3 different sites: a protected coastal lowland (altitude <10 m, trees T754, T789 and T794), an exposed xeric rocky ridgetop and boulder talus below (altitude 50-60 m, trees T43, T46, T961 and T970) and a mesic south-facing midslope up to *ca*. 75 m above tree line (altitude 65-75 m, trees T468, T542 and T543). Moreover, 3 saplings (G1-G3), selected once in the field, were collected near the trees harvested on the exposed ridgetop. Growth ring widths were measured with a Velmex micrometric table (pecision 2 μm). Mean width values were determined from measures taken along two opposite radii traced randomly but avoiding reaction wood.

2.5 Results

2.5.1 AERIAL VERTICAL PHOTOGRAPH ANALYSIS

During the 40 years spanning the two photo series, erect woody vegetation has expanded substantially. Close to 16 % of land surface essentially devoid of erect shrubs or trees in 1964 (cover <10 %) has been colonized by this vegetation at varying degrees by 2003, a near 29 % relative increase (Table 2.4). This considerable increase is well illustrated by repeat ground photography of areas that were analyzed on the aerial photos (Fig. 2.3). Newly colonized surfaces are mainly of discontinuous cover type, with a mean value of 37 % in 2003. If we consider 5 % as the mean cover of these surfaces in 1964 (mid value of <10 %), mean cover increase for these surfaces is 32 % in 40 years. There is some new continuous cover, indicating fairly rapid colonization and subsequent closure of erect shrub and/or tree canopy. Over a third of the 1964 discontinuous cover (7.4 % of total land surface analyzed) has experienced sufficient infilling to change its classification to continuous cover in 2003. Mean cover of these surfaces has passed from 59 % in 1964 to ≥90 % in 2003, an increase of 36 % (95 % considered as mean cover of the continuous cover class which is ≥90 %). Even 1964 discontinuous cover surfaces that have remained so in 2003 have been the object of partial infilling, passing from a mean cover of 47 % in 1964 to 62 % in 2003. Overall, it is more than 36 % of the analyzed area that has experienced a clear increase in erect woody vegetation from 1964 to 2003. This proportion attains 55 % if we exclude from the count the 1964 continuous cover and consider only surfaces available for colonization or infilling from 1964 onwards. As has been noted by Tape et al. (2006) in Alaska, three patterns of erect shrub and tree cover expansion were observed at the study site: new colonization, patch infilling and lateral growth of pre-established individuals.

Although an expansion of erect woody vegetation cover has been detected in all the environmental parameter classes, the extent of this expansion varies from one class to another, as seen through relative increase values (Table 2.4). More erect woody vegetation increase happened in higher elevation classes (above 70 m). Flatland and lowly inclined slopes have seen less relative increase then steeper slopes. As for exposure, southerly and easterly exposed areas have seen slightly higher relative increase. However, the greatest net increase happened on south-facing, 5-15 ° slopes between 20-70 m elevations. Although this elevation class has seen the least relative increase, the total surface it represents in the analyzed area is proportionately far higher than that of other elevation classes.

Table 2.4. Detected changes in erect woody vegetation cover in the vicinity of Kangiqsualujjuaq (Nunavik, Quebec) through comparative analysis of two vertical aerial photo series (1964 and 2003). Data are given first for total cover (discontinuous + continuous), which is then split by vegetation cover type (discontinuous: 10-90 % cover, continuous: ≥ 90 %). Data are also given for areas where sufficient infilling was detected for it to pass from a discontinuous classification in 1964 to a continuous one in 2003. Change is further detailed by environmental parameter classes. Cover values represent proportions of analyzed area occupied by either discontinuous or continuous erect woody vegetation, or by both types in the case of total cover. Relative increase represents net cover increase divided by the 1964 cover

	Total cover (%)			**Discontinuous cover (%)**				**Continuous cover (%)**				**Infilled areas (%)†**
	1964	2003	Relative increase	1964	2003	New cover*	Relative increase	1964	2003	New cover*	Relative increase	
Altitude (m)												
0-20	73,0	89,2	22,2	13,5	16,2	10,8	80,0	59,5	73,0	5,4	9,1	8,1
20-70	66,2	80,1	20,9	21,6	24,9	11,6	53,8	44,6	55,1	2,2	5,0	8,3
70-120	37,4	59,3	58,7	25,2	34,1	17,9	71,0	12,2	25,2	4,1	33,3	8,9
>120	23,2	38,4	65,5	20,0	32,8	15,2	76,0	3,2	5,6	0,0	0,0	2,4
Slope (°)												
0-5	64,5	77,1	19,6	19,0	23,8	11,1	58,7	45,5	53,3	1,5	3,3	6,3
5-15	47,6	66,1	38,8	22,3	29,5	15,4	69,2	25,3	36,6	3,1	12,2	8,2
15-30	44,7	63,5	42,1	22,4	28,2	14,1	63,2	22,4	35,3	4,7	21,1	8,2
>30	36,4	54,5	50,0	18,2	18,2	9,1	50,0	18,2	36,4	9,1	50,0	9,1
Exposure												
North	60,0	73,3	22,2	24,8	30,5	12,4	50,0	35,2	42,9	1,0	2,7	6,7
South	51,6	69,9	35,4	18,3	24,2	14,1	76,8	33,3	45,8	4,2	12,7	8,2
East	42,7	56,1	31,4	22,0	25,6	11,0	50,0	20,7	30,5	2,4	11,8	7,3
West	61,2	75,8	23,7	21,6	28,2	13,2	61,2	39,6	47,6	1,3	3,3	6,6
TOTAL	**54,9**	**70,7**	**28,9**	**20,7**	**26,5**	**13,2**	**63,8**	**34,2**	**44,2**	**2,6**	7,7	7,4

*These are newly colonized surfaces in the 2003 photo series, which have gone from <10 % cover of erect woody vegetation in 1964 to either a discontinuous or a continuous cover in 2003. Determination of these surfaces implies subtracting to both 1964 discontinuous and 2003 continuous cover, areas of 1964 discontinuous cover that have shifted to continuous in 2003. See Methods section for further details.

† Proportion of analyzed area which has passed from a discontinuous cover in 1964 to a continuous one in 2003.

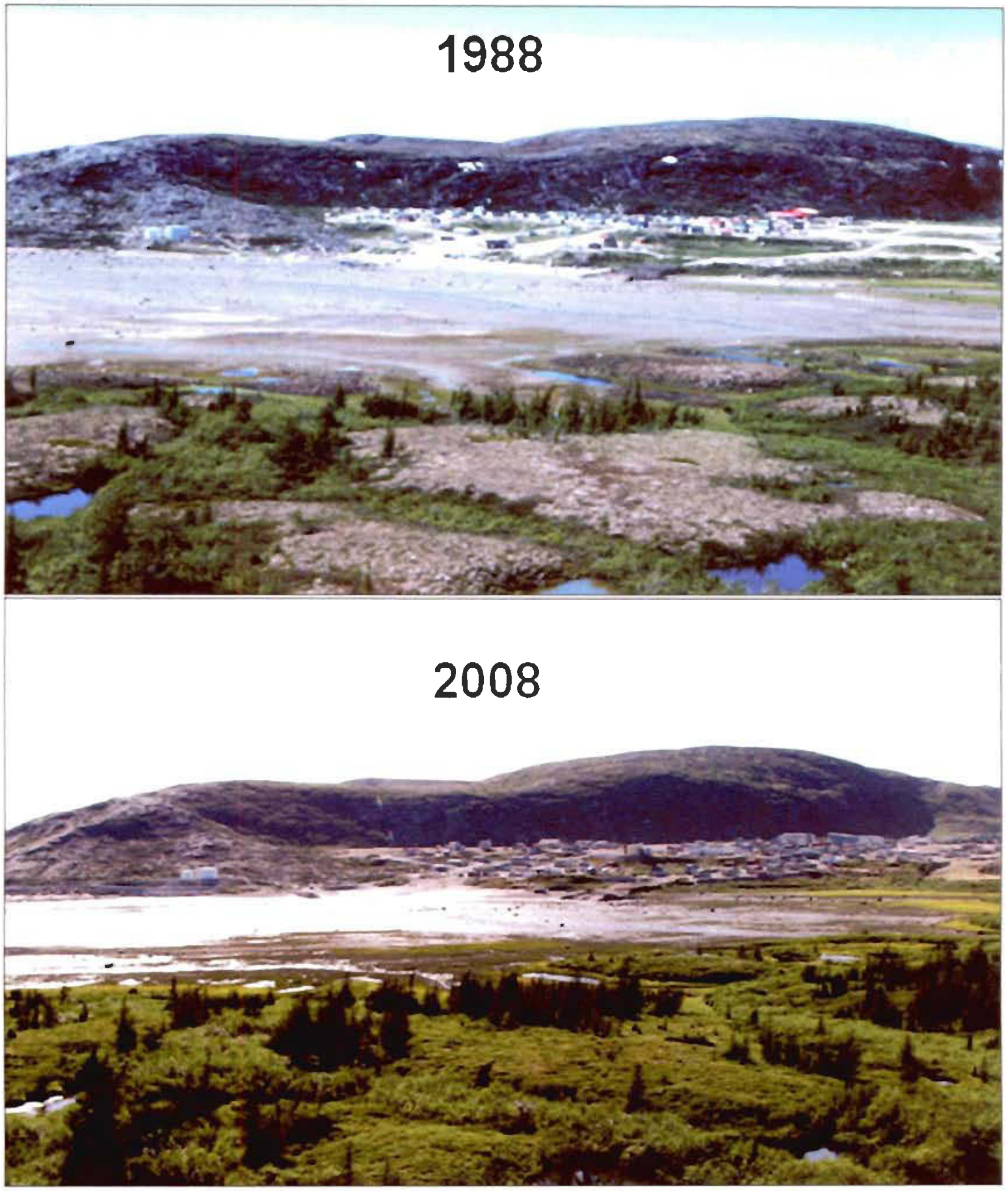

Figure 2.3. Repeat ground photography of a landscape near Kangiqsualujjuaq. View is from the east side of Akilasakallak Bay and shows substantial colonization of palsa summits by erect shrubs and trees in only 20 years. The 1988 photo was graciously provided by Marcel Blondeau and was taken at the end of July. The 2008 photo was taken August 7^{th}.

2.5.2 GROUND TRUTHING

Ground truthing consisted of 345 vegetation plots distributed in areas where an increase in erect woody vegetation was detected during photo analysis. These plots are divided as follows: 158 plots in new discontinuous cover, 75 plots in new continuous cover and 112 plots in areas of infilling (1964 discontinuous – 2003 continuous cover). Another 10 plots where made in areas that where still devoid of erect woody vegetation on the 2003 photos.

At the study site, ground truthing results clearly show that *Betula glandulosa* Michx. (dwarf birch) is the most common and abundant erect shrub species on surfaces where new colonization or an increase of erect woody vegetation has been detected. This species dominates the erect woody vegetation cover in 85 % of the 345 plots and occurs in 98 % of them (Fig. 2.4). Of the 294 plots where it is dominant, 75 are composed exclusively of this species. It is dominant in all the plots where slope is above 30 °, in 95 % of the plots situated above 120 m of altitude and in 91 % of the plots of northerly exposure. Aside from *B. glandulosa*, *Salix planifolia* Pursh (diamondleaf willow), *Salix glauca* L. var. *callicarpaea* (Trautv.) Argus (grayleaf willow), *Larix laricina* (Du Roi) K. Koch (eastern larch) saplings and *Rhododendron groenlandicum* (Oeder) Kron & Judd (Labrador tea) were also common, all occurring in more than 20 % of plots, although they dominated few (Fig. 2.4).

Cover values also serve to demonstrate the abundance of *Betula glandulosa* in areas where erect woody vegetation has increased. Mean cover of this species in plots where it occurs is 48 %. When only plots where it is dominant are considered, mean cover is but slightly higher: 52 %. Its abundance is thus globally high, be it dominant or not, which is not the case for other erect shrub and tree species. Although their mean cover may be high (between 22 and 70 %) in the few plots where they are dominant, it is low, between 2 and 23 % (mainly below 15 %), in the whole of plots where they occur.

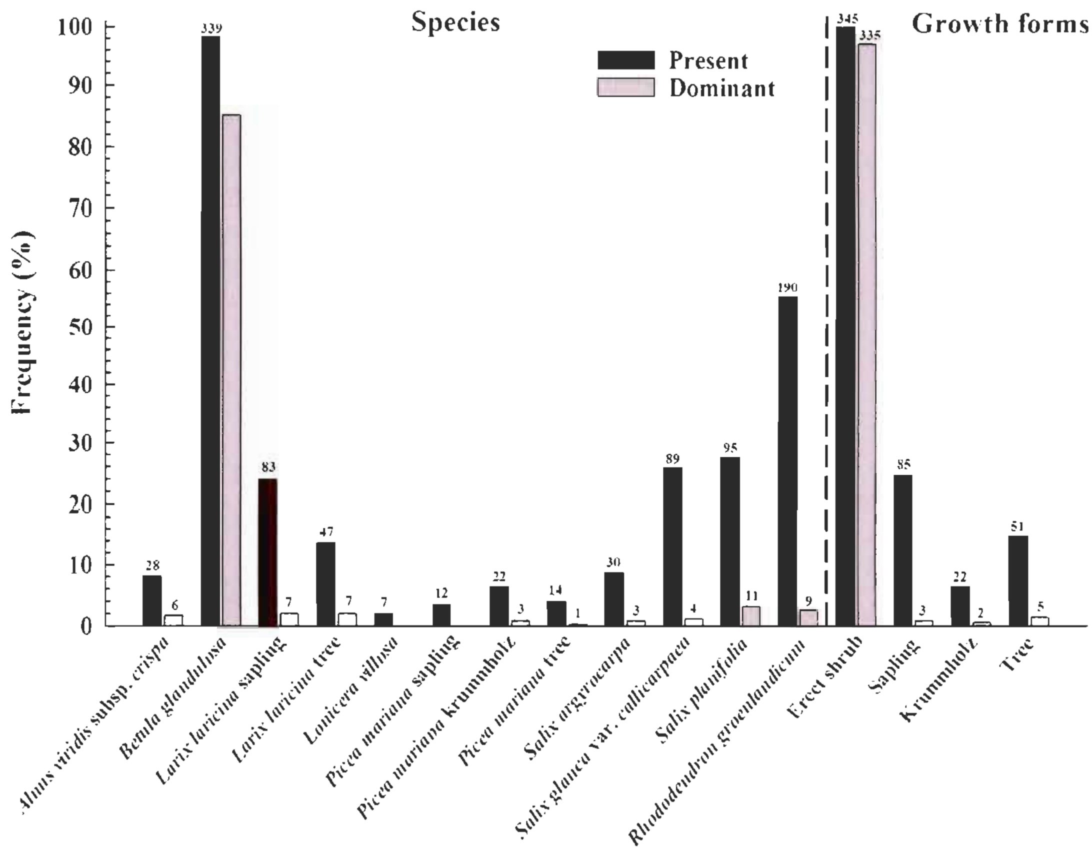

Figure 2.4. Proportion of total ground truthing plots (n=345) where each erect shrub and tree species is present, and where each species dominate the erect woody vegetation cover. Proportions are also shown by growth form (erect shrub, krummholz, tree) and stage (sapling). Straight *Picea mariana* $\geq$ 2.5 m high (Lescop-Sinclair and Payette, 1995) and *Larix laricina* > 5 m high are considered as trees; they are considered as saplings below these values. *L. laricina* does not form krummholz in the study area. Number of plots is given above bars.

The importance of *Betula glandulosa* in areas infilled or newly colonized by erect woody vegetation is reflected in the relatively high frequency of its seedlings, which occur in more than 37 % of the ground truthing plots (Fig. 2.5). These seedlings were usually found in disturbed areas, mainly on bare mineral soil related to frost boils and cryoturbation. However, some seedlings were observed through dense lichen cover on palsas and on wet brown moss beds overtopping mixed organic and loam deposits in fens. Seedlings of *Rhododendron groenlandicum* were also fairly frequent, occurring in more than 12 % of the plots. Overall, more than 41 % of plots contained erect shrub seedlings. These were essentially present in discontinuous cover plots, suggesting that closed canopy does not allow germination of the species involved. One surprising observation was high abundance of *Larix laricina* seedlings and saplings, mainly below 70 m (but some up to 120 m) in valley-sides above pre-existing forest cover and in lowland openings like palsa summits. One out of every four plots contained seedlings and/or saplings of this species; density of recruits surpassing $1/m^2$ in some plots. Abundance of seedlings and saplings of *Picea mariana* (Mill.) BSP (black spruce), the only other tree species present at the study site, was not nearly as high. They occurred in less than 4 % of the plots, mainly below 20 m of altitude, rarely up to 70 m.

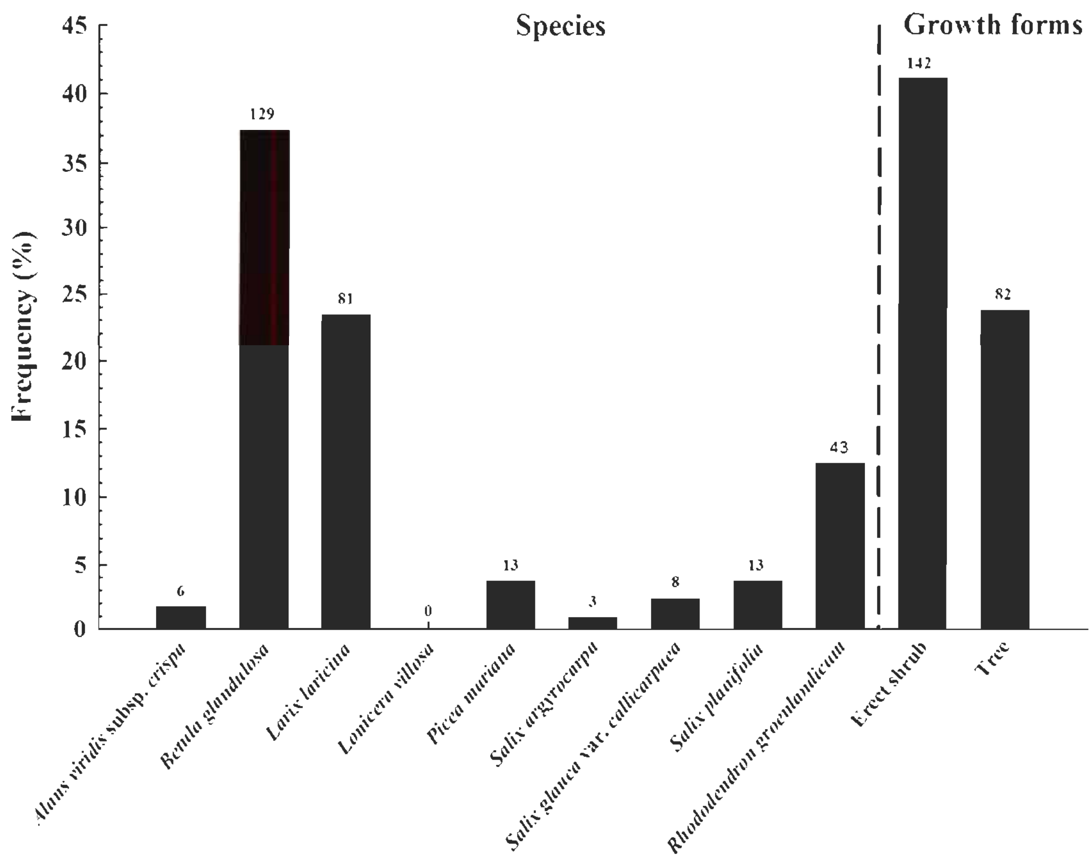

Figure 2.5. Proportion of total ground truthing plots (n=345) where seedlings of erect shrub species as well as seedlings and/or saplings of tree species occur. Proportions are also shown by growth form. Height for *Picea mariana* to be considered as a sapling is ≤ 2.5 m with a straight growth and ≤ 5 m for *Larix laricina*. Number of plots is given above bars.

Less than a third (29 %) of the analyzed area showed no colonization by erect woody vegetation on the 2003 photos. The 10 plots randomly positioned in these areas consisted essentially of 1) boulder fields, 2) rock outcrops, 3) exposed hilltop plateaus with abundant boulders and bare soil and 4) sedge fens found mainly on valley floors and hillside nivation terraces. Most uncolonized surfaces are made up of the last two habitat types.

2.5.3 EXPLORATORY DENDROCHRONOLOGY

All trees harvested for exploratory dendrochronology turned out to be *Larix laricina*. Consequently, saplings of the same species were collected for analysis. The 10 trees ranged from 49 to 69 years of age and the 3 saplings were between 14 and 27 years old. Growth ring analysis showed a general trend towards wider rings from *ca.* 1990 onwards (Fig. 2.6). All trees have similar patterns of relatively narrow growth rings during the first 30 to 50 years after establishment, followed by a sharp increase in ring width during the last two decades or so; the widest rings observed during the last decade. Saplings do not have this pattern, growth ring widths showing a gradual and continuous increase from year of establishment onwards, with sapling G2 having relatively wide rings from the start.

2.6 Discussion

Comparative analysis of old and recent aerial vertical photos of land surface surrounding the village of Kangiqsualujjuaq has enabled us to detect a substantial increase of erect woody vegetation cover in this Low Arctic site, attributable mainly to erect shrubs. This find is supported by other indications of change, such as local ecological knowledge, repeat ground photography, exploratory dendrochronology, regional-scale NDVI analysis and climate data. However, this land cover change is not homogenous at the landscape level and some erect shrub and tree species are responsible for greater amounts of cover increases than others.

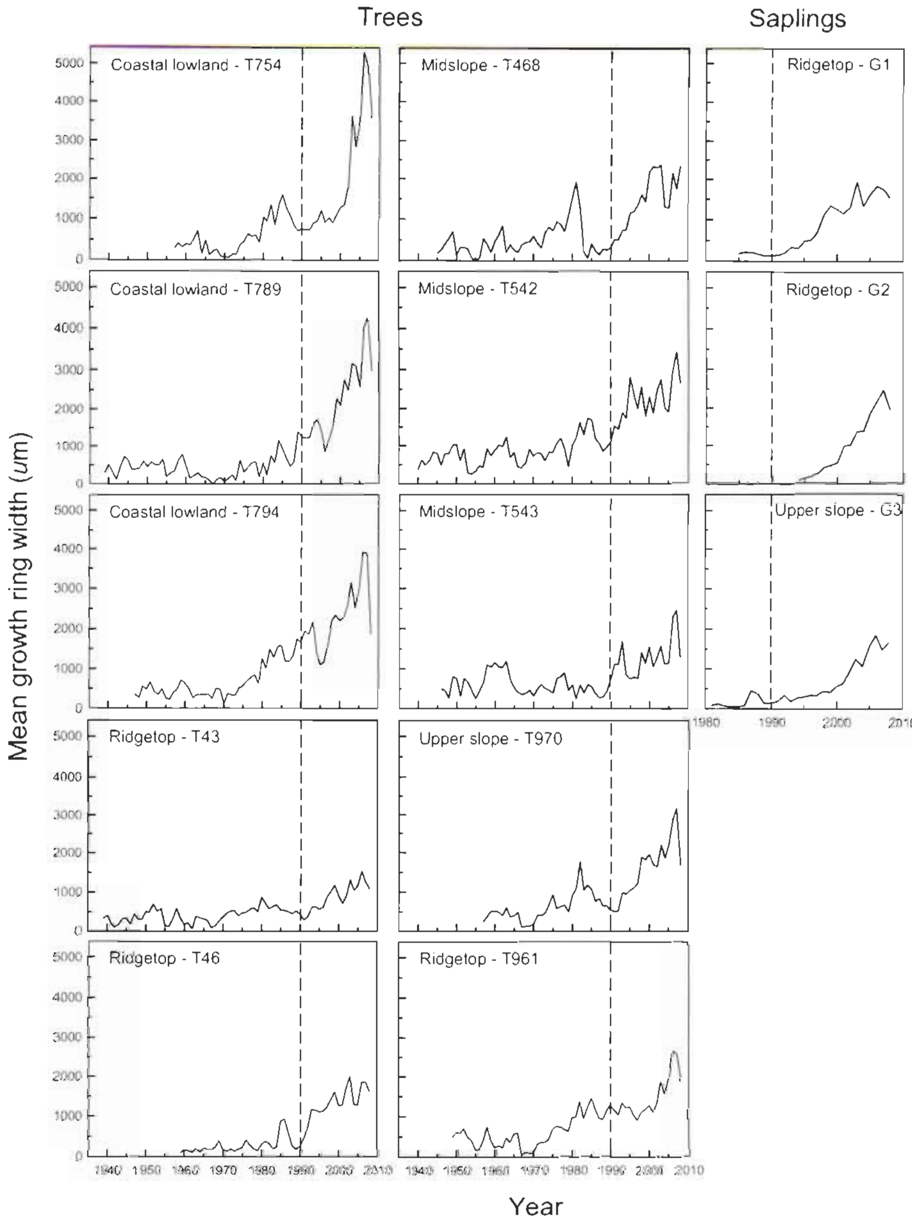

Figure 2.6. Mean growth ring width of 10 trees and 3 saplings of *Larix laricina* harvested in 2008 near Kangiqsualujjuaq (Nunavik, Quebec) on the eastern side of Akilasakallak Bay. Ring width represents the mean of two measures taken randomly on cross-sections. Trees T754, T789 and T794 grew on protected coastal lowlands; T468, T542 and T543 on a mesic south-facing midslope; T970 and G3 on a subxeric east-facing protected upper slope on the edge of treeline; T43, T46, T961, G1 and G2 on a subxeric to xeric exposed rocky ridgetop.

2.6.1 LANDSCAPE TYPES AND MAIN SPECIES

The main landscape types available for new colonization have experienced the largest relative increase of erect woody vegetation. These mostly consisted of southerly and easterly exposed mid to upper slopes of 5 to 30° inclination. Less inclined and loweraltitude areas were already fairly well vegetated with erect shrubs and trees in 1964. In addition, thermal regime and snow accumulation are higher on southern and eastern slopes due to north and northwest prevailing winds, which sweep over the cold waters of nearby Ungava Bay before they reach the study site. Although greater woody increase in these landscape types could be expected, our results suggest an amelioration of conditions in sites that were previously not or less favourable for erect shrubs or trees. Since an expansion of erect woody vegetation has been detected in all landscape types, it can be assumed that there has been a general improvement of environmental conditions at the study site, and most probably at a larger geographical scale. The only habitats which have seemingly remained uncolonized by erect shrubs and/or trees until now are ones which are too dry and lack loose substrate, like rock outcrops and boulders fields, or too wet and subject to high interspecific competition, like some sedge fens. However, we observed that even some of these fens, in protected lowlands, are being colonized by *Larix laricina*.

Ground truthing has shown that the recent increase of erect woody vegetation in the vicinity of Kangiqsualujjuaq was essentially attributable to one species: *Betula glandulosa*. This species is probably the most common and abundant erect shrub in the Canadian Eastern Low-Arctic. Around Kangiqsualujjuaq, it has the highest ecological amplitude of all erect shrubs present, occurring in all types of habitats, from wet and peaty to dry, rocky and exposed. Based on shrub thickets already present on the 1964 photos, of which many were investigated during field work, *B. glandulosa* was probably also the most common and abundant erect shrub at the study site back in 1964. *B. glandulosa* may be the erect shrub which is able to most efficiently respond to an upgrade of environmental conditions, as was found for *Betula nana* L. (arctic dwarf birch) in Alaska and Iceland (Bret-Harte et al., 2001, 2002; Jonsdottir et al., 2005; Wahren et al., 2005) following experiments using OTCs. In birch hummock tundra around Daring Lake (Northwest Territories, Canada), an ongoing experiment using greenhouses also shows considerable growth response of *B. glandulosa* to warming (P. Grogan, unpubl. data).

The contribution of all willows to global increase is fairly low. *Salix planifolia* and *Salix argyrocarpa* Anderss. (Labrador willow) are responsible for some detected increase only on lowland peaty soil and alluvium. Unlike the situation in Alaska where *Alnus viridis* (Chaix) DC. *sensu lato* (green alder) played an important role in erect shrub increase (Sturm et al., 2001b; Tape et al., 2006), its contribution in the study area is negligible, being mainly restricted to favourably exposed slopes along the George River. In Nunavik, *A. viridis* is only sporadic above the forest tundra vegetation subzone, up to *ca.* 60°N in river valleys. At the study site, climatic factors evidently limit its distribution and abundance; a situation that may change in the near future not only for green alder but also for other boreal species like *Rhododendron groenlandicum* and, as is already the case, *Larix laricina*. Moreover, the high frequency of erect shrub seedlings and *L. laricina* saplings in the ground truthing plots suggests that colonization and infilling is an ongoing process, even though precise seedling abundance data is not available for shrub species. Further expansion is therefore expected, especially of *Betula glandulosa*, if favourable climatic conditions persist.

2.6.2 *LARIX LARICINA* EXPANSION AND TREE LINE MOVEMENT

Field work has revealed a remarkable abundance of *Larix laricina* seedlings and saplings on hillsides above tree limit and in openings of previously forested land, like palsa summits. The fairly recent colonization of tundra by numerous *L. laricina* recruits at the study site supposes that current climatic conditions allow for adequate seed maturation and viability, coupled with a high rate of survival and vigorous development following establishment; all of which may have limited *L. laricina* expansion or recovery following past disturbances such as fire or *Pristiphora erichsonii* Hartig (larch sawfly) outbreaks. The key role played by temperature in proper seed maturation, essential to vigorous germination, has been documented for several boreal coniferous tree species (Henttonen et al., 1986; Farmer, 1997; Sirois, 2000). Another factor that may have limited *L. laricina* expansion in the past is intense grazing pressure by large populations of herbivores, such as the Rivière George caribou herd (RGCH) which attained peak numbers in 1993 thereafter followed by a rapid decrease (Couturier et al., 2004). However, *L. laricina* contribution to nutrition of caribou (*Rangifer tarandus* L.

subsp. *caribou* Gmelin) of the Rivière George herd is very low (Crête et al., 1990) and past expansion cannot have been prevented solely by caribou trampling of seedlings and low saplings.

Larix laricina recruits were mainly found to colonize mesic to subhumid dwarf shrub-lichen-moss tundra on the lower half of slopes, although they also occurred in sedge fens and on dry lichen covered palsas. Furthermore, *L. laricina* seems able to colonize even dense *Betula glandulosa* thickets, although in a lesser magnitude than more open tundra. *L. laricina* expansion was also observed by local residents along the George River upstream from the village. However, woodlands are very sporadic at this latitude and favourable sites are fairly restricted, thus limiting the overall possibility of *L. laricina* expansion. Nevertheless, if proper climatic conditions persist, the landscape of valleys where some *L. laricina* previously grew may change considerably in the future, as low shrub tundra, and even *B. glandulosa* thickets, are gradually overtaken and evolve into open *L. laricina* woodland. Comparison between the 1964 and 2003 photos has shown a great deal of new trees in 2003. Field work revealed that all new trees are *L. laricina*. Overall, the abundant new trees on hillsides coupled with the numerous seedlings and saplings seen in the field indicate that local tree line is migrating upslope.

This is not the first report of an apparent rise of altitudinal tree line in northern Quebec, something that was also observed by Gamache and Payette (2005) for *Picea mariana* along a transect spanning the forest-tundra of eastern Nunavik. In the southern part of the forest-tundra, this rise operated through establishment of seed-origin *P. mariana* while in the northern part it was due to vertical growth of stunted individuals. The latter case has also been observed on the east coast of Hudson Bay, where it was responsible for a longitudinal tree line shift towards the coast (Lescop-Sinclair and Payette, 1995). Such a response of *P. mariana* to climate warming, in the form of a change from a stunted to a straight growth, seems to be also the case in our study area, where seedlings are very scarce and restricted to valley bottoms.

A contrasting result to our own was found by Morin and Payette (1984) in a study on *Larix laricina* expansion at the northern limit of the forest-tundra and latitudinal tree line along the Leaf River, on the west side of Ungava Bay. Their results showed very low *L. laricina* density in ecotones bordering *L. laricina* stands. Moreover, they reported an absence of *Picea mariana* seedlings in these ecotones, something which has also been observed at our study site. The authors concluded that climate warming since the end of the Little Ice Age probably resulted more in the consolidation of preexisting tree populations rather than in the rise of tree line. Considering the accelerated warming of many arctic areas in recent years, this situation has possibly changed and revisiting the area may prove to be highly interesting.

2.6.3 EXPLORATORY DENDROCHRONOLOGY

The ten *Larix laricina* harvested for dendrochronological analysis were visible on the 2003 photos but not on the 1964 ones and were thus considered, prior to aging, as trees newly established between 1964 and 2003. However, all individuals being over 40 years of age, they were already established when the old photos were taken, but still small enough to escape detection although some were already 25 years old in 1964. Growth ring analysis showed comparatively narrow rings and less marked fluctuations in widths during the first 30 to 50 years after establishment. This period was followed by a rapid and substantial increase in ring width after 1990. This was visible in all trees even though they were collected in different habitat types with contrasting moisture regimes, exposure and altitude. Saplings showed relatively wide growth rings and a steady increase in growth rate nearly from the start, suggesting that the initial period of slow growth found in tree cross-sections is more closely linked to past climate than to competition by surrounding vegetation and/or time required for proper establishment. The marked increase in radial growth found in both tree and sapling cross-sections for the past two decades or so points to a general upgrade of climatic conditions during this period, in particular warmer temperatures.

2.6.4 INFLUENCING FACTORS

2.6.4.1 Human activity

Permanent human presence on the shores of Akilasakallak Bay on the east side of the George River dates back to the late 1950s – early 1960s when the construction of the actual village started. Since then, human activity has had impacts on erect woody vegetation through various uses; impacts that may have locally influenced its evolution and extent. This has been assessed mainly through interviews with community Elders (A. Cuerrier, unpubl. interviews).

One of the impacts is the harvest of trees in order to build and heat houses. Wood used to build houses initially came from upstream of the George River where trees were larger, and trunks were hauled by boat to be processed by a sawmill installed on the beach of Akilasakallak Bay. Later on, materials used to build the houses were brought in from the south. A generator was installed in the village by 1960-1961. Some wood was harvested for fuel during winter by dog sled a few kilometers from the village on the other side of the river. Wood near the village has also been used for building tipis, kayaks, sleds (qamutik) and boats (umiak). During fieldwork, both old and recent signs of woodcutting were frequently noticed in woodlands east of Akilasakallak Bay, opposite from the village. However, these were always sporadic and consisted of few or unique stumps mainly found on the edge of wooded areas. These signs of woodcutting are undiscernible on both the 1964 and 2003 photos and the general outline of forested land is essentially the same on both photo series.

Twigs of erect shrubs, dead trees and branches are used as kindle while camping or during a day out on the land, but its impact on erect woody vegetation cover is insignificant around the village. Greater snow accumulation on the sides of road or house embankments may have favoured shrub growth but surfaces affected by this are quite small and excluded from analysis. Human activity may have influenced the assessment of erect woody vegetation increase both in the way of a slight underestimation due to harvest or overestimation linked to caribou avoidance of surrounding areas (*cf.* next heading). Overall, human disturbance in the study area is low or non-existent aside from the village site itself and areas in proximity to roads. Hence, the influence of human activity on the evolution of erect woody vegetation cover and its detected increase in the vicinity of Kangiqsualujjuaq appears to be negligible.

2.6.4.2 Herbivory

The study area is located in the summer range of the Rivière George caribou herd (RGCH), which occupies the eastern half of Nunavik (Couturier et al., 2004). Through trampling and grazing, this large herbivore herd greatly impacts the vegetation cover. Severe degradation of lichen cover has been documented in the summer range of the RGCH (Boudreau and Payette, 2004a) and decreased ground cover and leaf biomass of *Betula glandulosa* in grazed stands has been noted in calving grounds on either side of the George River (Manseau et al., 1996). The RGCH has been the object of considerable population fluctuations in the last century. Historical information suggests that caribou were fairly abundant in northern Quebec/Labrador in the 1880s, but numbers declined sharply between 1890 and 1910, for unknown reasons (Messier et al., 1988). In 1954, population estimates of the RGCH following nonsystematic aerial survey was only *ca.* 5 000 (Messier et al., 1988) and *ca.* 62 000 animals 9 years later, in 1964, following strip census and extrapolation to total area. Although confidence intervals are not available for theses numbers and their precision is subject to discussion, they give an idea of caribou numbers in these years. In 1980, the herd attained 295 000 ± 29.0 % caribou. The 2001 census revealed that the herd still counted 385 000 ± 28.0 % individuals 8 years after peak level of nearly 800 000 ± 18.9 % in 1993 (Couturier et al., 1996, 2004). The rapid demographic downfall in the 1990s resulted in release of grazing pressure, especially on one of its preferred forage, *B. glandulosa* (Crête et al., 1990). Although erect shrub growth and expansion was certainly constrained during periods of high caribou abundance, the detected increase of erect woody vegetation in the vicinity of Kangiqsualujjuaq cannot be imparted to this grazing pressure release. If caribou abundance and associated grazing had such a key influence on the extent of erect woody vegetation cover (mostly erect shrubs), one would expect the cover to be greater in 1964 than in 2003, when only 2 years before the population level was more than 6 times higher than in 1964.

In the study area, proximity to human settlement may have greatly limited caribou occupation of surrounding areas and associated grazing impacts. The study area did however include areas that were fairly remote and isolated from noise disturbance before the construction of roads in the late eighties and the extent of infrastructures has remained low until fairly recently. Moreover, local residents attest that caribou used to pass very close to, and even directly in, the village. This has changed since the mid 1990s, as caribou now pass further south from the village. Caribou may never have remained long enough in the vicinity of the village to have notable impacts on the vegetation cover. This may also have been the case even before human settlement, as higher grazing pressure probably occurs on calving grounds, the north-central limit of which was situated slightly south of the village area even during peak numbers (Crête et al., 1991; Couturier et al., 1996). However, NDVI analysis over coastal and inland areas southeast and east of Ungava Bay has shown considerable shrub increase between 1988 and 2002, even in northern parts of the RGCH calving ground which were included in the analysis (W. Chen et al., submitted). As such, our local-scale results and those obtained through NDVI analysis at a regional-scale suggest that caribou grazing, even when in high numbers, may not significantly limit erect shrub expansion at a large scale in the shrub tundra vegetation zone.

During high abundance of caribou at the turn of the 1990s, the destruction of lichen cover associated with grazing and trampling may have played a positive role in erect shrub expansion, especially of *Betula glandulosa*. Many authors have reported partial or complete destruction of lichen cover in the summer range of the RGCH (Manseau et al., 1996; Morneau and Payette, 1998; Boudreau and Payette 2004a, b; Theau and Duguay, 2004), resulting in the degradation of superficial organic layers and subsequent exposure of mineral soil (Boudreau and Payette, 2004a). Field work around Kangiqsualujjuaq has shown that *B. glandulosa* seedlings are much more abundant on bare soil, be it mineral or organic. Consequently, the opening of the lichen cover by caribou activity, coupled with a possibly higher abundance and quality of *B. glandulosa* seeds in recent years, may have favoured new *B. glandulosa* establishment before the slow recovery of the lichen cover, followed by greater survival of recruits in the 1990s linked to decreased grazing and trampling.

2.6.4.3 Climate warming

A recent temperature rise, probably accompanied by a lengthening of the growing season, seems to be an important factor in explaining the expansion of erect woody vegetation in the study area. This seems to be also the case for the rise of altitudinal tree lines detected in northern Quebec (Gamache and Payette, 2005). Mean annual temperature data from 1966 to 1995 showed a cooling trend in the Canadian Eastern Arctic (Serreze et al., 2000), which was reflected in permafrost temperatures (Allard et al., 1995; Wang et al., 1995). However, this trend has since reversed, at least for many areas of the Canadian Eastern Arctic, as evidenced by both air (Fig. 2.7) and ground (Allard et al., 2007) temperature data. Mean annual temperatures plotted for 6 Canadian Eastern Arctic localities show a general warming trend since 1993 at all sites. Moreover, the highest annual mean temperature on record was attained after 2000 at all localities and many values between 1993 and 2008 are among the highest ever recorded there. This recent temperature rise matches with growth ring widths of *Larix laricina* trees and saplings harvested around Kangiqsualujjuaq for exploratory dendrochronology (Fig. 2.6).

2.6.5 LIMITS OF PHOTOINTERPRETATION AND MAPPING

The level of increase determined in this study is considered a minimum value since limits of the method used in this study pertain to two factors that both can lead to underestimation of erect woody vegetation increase. Firstly, all areas covered by erect shrubs and/or trees that were inferior to 100 m^2 were overlooked. Nonetheless, due to initial doubts about their possible inclusion, contours of the larger areas below the 100 m^2 limit were traced during analysis before surface determination. These areas were later removed before comparative analysis but their initial inclusion enabled us to calculate their total surface, which was less than 2 hectares (<0.3 % of total area analyzed) for both 1964 and 2003. This demonstrates that their initial inclusion in the analysis would not have had a significant impact on total increase assessment. The second factor is the capacity of erect shrub detection on the aerial photos, mainly linked to height of erect shrub individuals coupled with vegetation cover. Isolated individuals and small thickets lower than *ca.* 25 cm, which are either not fully grown or restricted by environmental conditions, are almost impossible to detect when they are found through a dense herbaceous and/or low ericaceous cover, which have a similar shade on the photos.

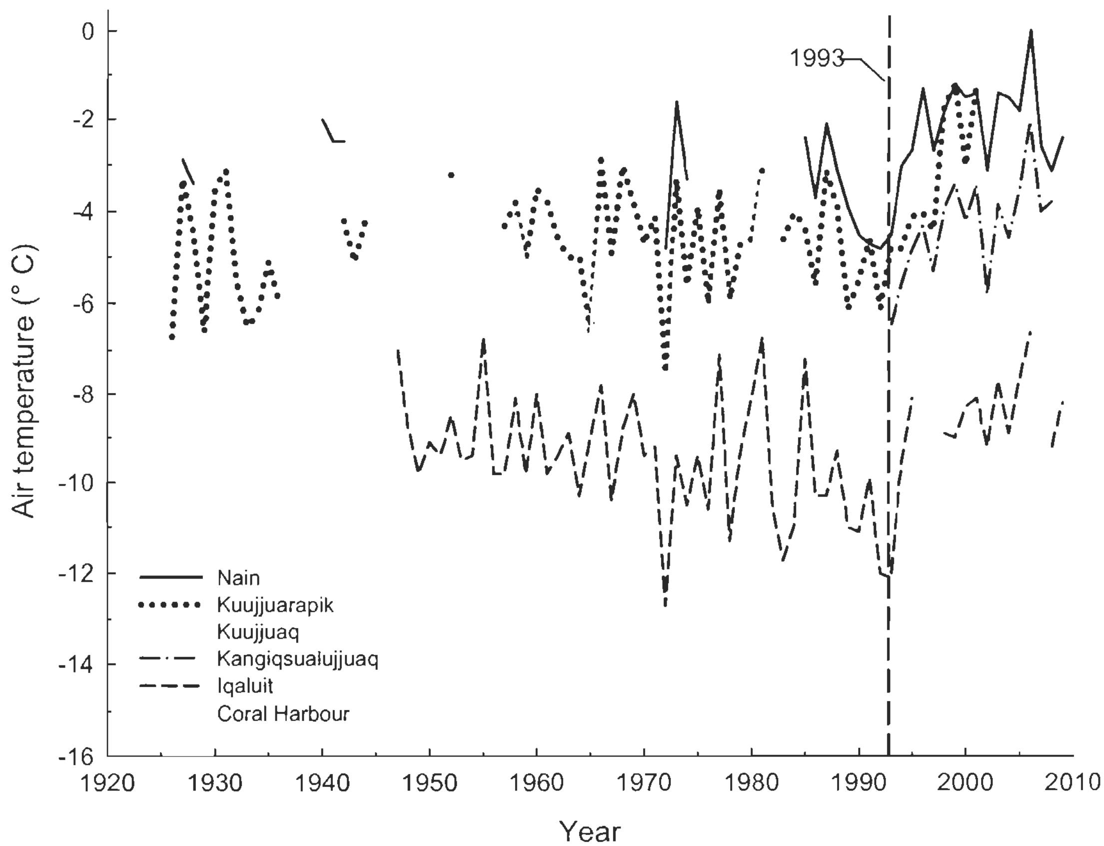

Figure 2.7. Mean annual temperatures of six eastern Canadian Arctic localities : Nain (Labrador, 56°33'N-61°41'W; 1927-2009 with incomplete data from 1927 to 1984), Kuujjuarapik (Quebec, 55°17'N-77°45'W; 1926-2009 with incomplete data from 1937 to 1957, 2002 to 2004 and 2006 to 2008), Kuujjuaq (Quebec, 58°06'N-68°25'W; 1948-2009), Kangiqsualujjuaq (Quebec, 58°43'N-66°00'W; 1993-2008), Iqaluit (Nunavut, 63°45'N-68°33'W; 1947-2009 with missing data for a few years) and Coral Harbour (Nunavut, 64°11'N-83°22'W; 1946-2009 with missing data for a few years). Source of raw data is Centre d'études nordiques (Laval University) for Kangiqsualujjuaq and Environment Canada for all other localities. Parallelism of all the curves is remarkable and they all show a similar trend of higher mean annual temperatures since 1993.

In general, photointerpretation and field validation closely matched. In the few cases where photo and field classifications did not concord, plots (and corresponding polygons) were located on richly vegetated sedge fens which have a dark shade on the aerial photos and were interpreted as continuous (≥90 %) erect shrub cover. Although these fens harbour some erect shrubs (mainly *Betula glandulosa*), their distribution is patchy and total cover not high enough for it to be classified as continuous.

Overall, comparative vertical aerial photo analysis has enabled us to detect a substantial erect woody vegetation increase in the vicinity of Kangiqsualujjuaq (northern Quebec) for the period 1964 to 2003, during which a minimum estimate of 55 % of available surfaces were affected by new colonization or infilling. This increase is essentially due to *Betula glandulosa* and may have been caused by the combined effect of warmer temperatures and opening of the lichen cover by caribou trampling and grazing. In the case of *Larix laricina* however, it appears that a recent upgrade of climatic conditions may be the preponderant factor explaining the abundance of recruits and the associated rise of altitudinal tree lines, as it seems able to establish itself through any type of vegetation cover except high dense thickets of *Alnus viridis* subsp. *crispa* or *Salix planifolia*. This recent upgrade of environmental conditions is also suggested by dendrochronological analysis, which shows a marked increase or *L. laricina* radial growth during the past two decades or so. Although the studied surface is limited from a global point of view, regional-scale satellite image analysis of land surface east of Ungava Bay for the period 1988-2002 (W. Chen et al., submitted), which includes our study site, is consistent with our results. Considering the general warming trend since the end of the Little Ice Age, part of the detected erect shrub and tree expansion could be expected. However the amount of change observed in this study for such a relatively narrow time span (40 years) appears quite high and suggests a recent acceleration in land cover evolution towards shrubbier tundra and its local colonization by trees at the southern edge of the Arctic. This is supported by local ecological knowledge, temperature data, the abundance of *L. laricina* young recruits and growth ring widths of trees, and by repeat ground photography with a 20 year interval between old and recent photos. A similar increase of erect woody vegetation may be expected in other Canadian

Eastern Arctic areas of comparable latitude and environmental conditions, as suggested by NDVI analyses of northern Canada. However, this hypothesis must be further supported by fine scale studies of other Canadian Eastern Arctic localities, in association with satellite image analysis.

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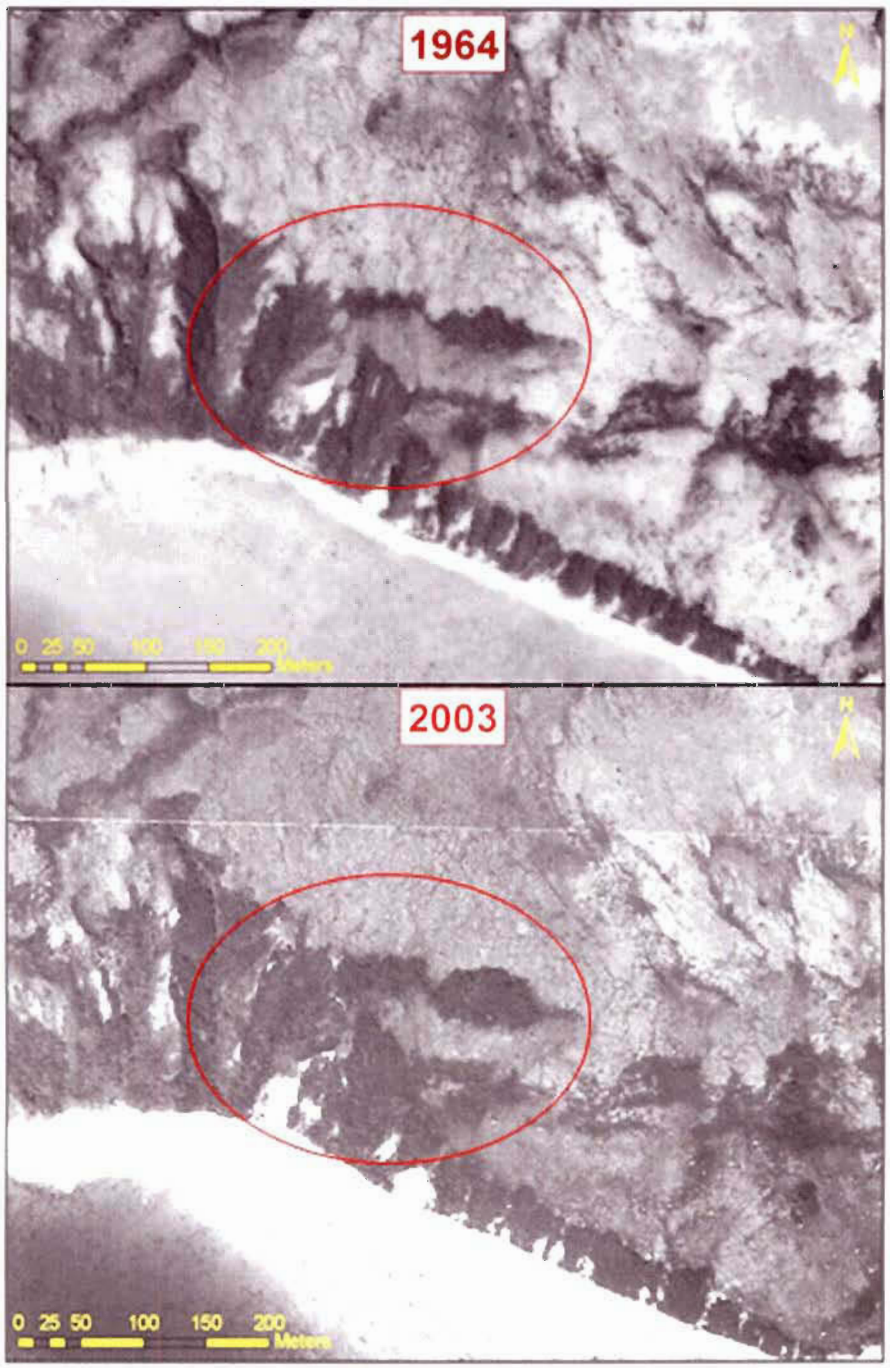
ANNEXE 1

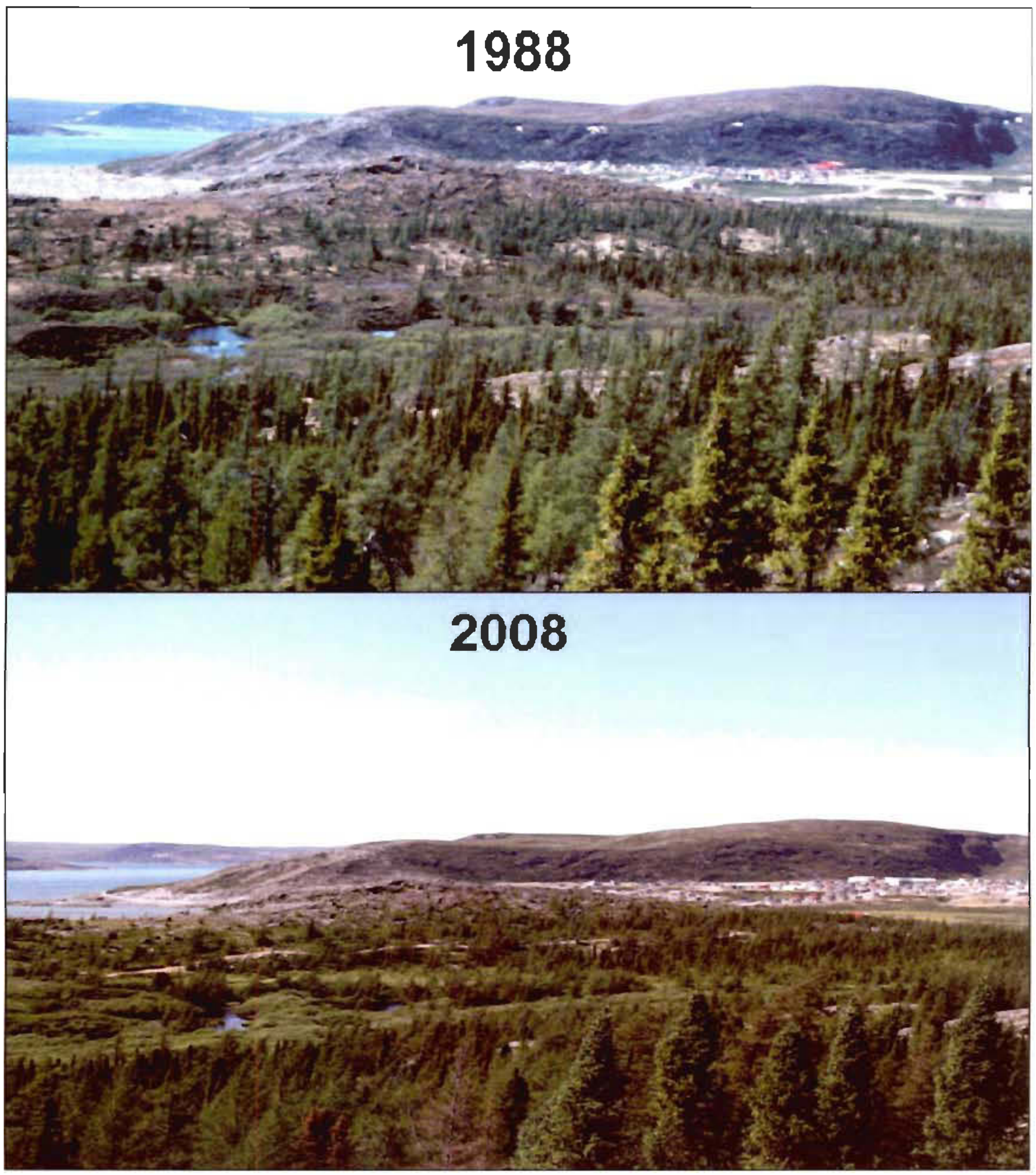
Portions de photographies aériennes verticales des environs de Kangiqsualujjuaq (Nunavik, Québec) représentant le même secteur en 1964 et en 2003, où l'on constate une expansion du couvert d'arbustes érigés au cours des 40 ans séparant les deux images. Source de l'arrière-plan, 1964: photographie aérienne A18324-13, Photothèque nationale de l'air, Ressources naturelles Canada; 2003: orthophotographies 24I12-1502 et 1602, ©Gouvernement du Québec, ministère des Ressources naturelles et de la Faune.



ANNEXE 2

Photographies obliques répétées illustrant le même paysage situé au nord-est du village de Kangiqsualujjuaq, en 1988 et 20 ans plus tard, en 2008.

On distingue une densification du couvert ligneux érigé dans le fond de la vallée, une augmentation de la hauteur des arbres à l'avant-plan, une colonisation de palses organiques par des arbustes érigés (moitié gauche de la photo, au milieu) et l'établissement de nouveaux arbres sur le sommet de la colline rocheuse (à gauche au milieu, en-dessous du plan d'eau). La photo de 1988 a été prise à la fin de mois de juillet par Marcel Blondeau. Celle de 2008 a été prise par l'auteur le 2 août.



ANNEXE 3

Directives aux auteurs, revue *Arctic, Antarctic and Alpine Research*

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Include lengthy statistical data subordinate to the text.

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