RÉHABILITATION DE TOURBIÈRES INDUSTRIELLES CONTAMINÉES PAR L'EAU SALÉE : VÉGÉTATION DE MARAIS SALÉS ET AMENDEMENTS

Mémoire

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Résumé

Les bogs côtiers peuvent être envahis par l'eau de mer. Ils demeurent ensuite sans couvert végétal en raison des conditions salines et acides, de haute nappe phréatique et de faible disponibilité des nutriments. On veut accélérer la colonisation végétale de ces bogs en utilisant des plantes de marais salés et des amendements. Une expérience terrain testait si la roche phosphatée et la chaux dolomitique pouvaient améliorer la croissance de: (1) transplants de *Carex paleacea* et (2) *Spartina pectinata*, (3) transferts de diaspores récoltées en juillet et (4) août et (5) un témoin. Une expérience en serre testait les doses de chaux nécessaires pour *C. paleacea* et *S. pectinata.* La roche phosphatée a amélioré la croissance de tous les matériaux végétaux puisque le P est rare dans les bogs. La transplantation de *C. paleacea* a entraîné les couverts végétaux et les biomasses aériennes les plus élevés et le transfert de diaspores a entraîné une diversité d'espèces supérieure. La chaux n'a pas amélioré la croissance de la végétation. On recommande l'application de roche phosphatée, la transplantation de *C. paleacea* et le transfert de diaspores de marais salés.

Abstract

Coastal cutover bogs are prone to sea water contamination. It keeps them unvegetated because of salinity, acidity, high water table level and low nutrients availability. We want to encourage plant colonization of those bogs using salt marsh vegetation and amendments. A field experiment aimed to examine whether rock phosphate (P_2O_5) and dolomitic lime (CaO.MgO) improve growth of (1) *Carex paleacea*, (2) *Spartina pectinata* transplants, (3) salt marsh diaspores transfer of different maturity - July, (4) August and (5) a bare peat control. A greenhouse experiment tested the lime dose needed by *C. paleacea* and *S. pectinata*. Results showed that P improved growth of all plant treatments because of P deficiency in bogs, while *C. paleacea* resulted in greater vegetation cover and aerial biomass, and diaspores transfer in higher diversity. Lime failed to improve vegetation growth. Rehabilitation should be done using P, salt marsh diaspores transfer and *C. paleacea* transplantation.

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Chapitre 1 : Introduction générale aux écosystèmes de tourbières

Les tourbières sont des milieux humides où les débris végétaux s'accumulent sous forme de tourbe, car le taux de décomposition est inférieur à la productivité des plantes. Une tourbière s'initie souvent par un milieu humide de type minérotrophe, qui peut être suivi de celui de bog (tourbière ombrotrophe). Les fens, où l'accumulation de débris végétaux demeure près du niveau du sol minéral adjacent, sont alimentés par l'eau du ruissellement du sol ainsi que des précipitations. Dans les bogs, l'accumulation de débris végétaux est plus importante et avec le temps, la surface de la tourbière s'élève, ce qui l'isole de l'eau du ruissellement du sol. Les bogs sont donc uniquement alimentés par les précipitations atmosphériques, ce qui en fait des milieux humides pauvres en éléments nutritifs. Ils sont composés principalement de sphaignes, qui peuvent être considérées comme des ingénieures d'écosystème (Rochefort, 2000). Les tourbières émettent du méthane (CH_4) mais ont une grande capacité de séquestration de carbone, en raison de la matière organique végétale qu'elles accumulent (Harriss *et al.* 1985; Clymo *et al.* 1998*; Moore et al.* 1998). Les conditions acides et anaérobies ralentissent l'action des microorganismes de la décomposition, ce qui leur permet d'accumuler une épaisseur de tourbe allant de 30 cm à plusieurs mètres, au cours de milliers d'années (Ingram, 1978; Clymo, 1984). Les principaux biens et services écologiques des tourbières sont la possibilité d'y pratiquer la cueillette des petits fruits et la chasse, elles peuvent servir d'archives paléoécologiques, elles augmentent la biodiversité de leur région et les tourbières minérotrophes, qui souvent situé dans le bas des bassins versants, peuvent régulariser l'écoulement des eaux (Gorham, 1991; Parkyn *et al.* 1997; Calmé *et al.* 2002).

Depuis la fin des années 60 c'est la technique de récolte par aspiration qui est principalement utilisée pour extraire la tourbe à des fins horticoles. À cette fin, des canaux de drainage sont creusés pour assécher la tourbière et permettre à la machinerie d'y circuler. La végétation de surface est supprimée, puis la tourbe sèche est récoltée à l'aide d'immenses aspirateurs. À la suite de ce processus, les tourbières sont dénudées de végétation et de propagules qui pourraient permettre un retour à l'écosystème d'origine (CSPMA, 2010). Le milieu demeure donc dénudé durant de nombreuses années et le retour des sphaignes est difficile (Lavoie & Rochefort, 1996). Les producteurs de tourbe du Canada se sont engagés à un programme de développement durable et sont donc tenus de restaurer les tourbières exploitées afin de rétablir leurs fonctions d'origine (GNB, 2010; CSPMA, 2011). À cette fin, une approche de restauration écologique par transfert muscinal élaborée par le Groupe de Recherche en Écologie des Tourbières (GRET) est appliquée (Quinty & Rochefort, 2003; Rochefort *et al.* 2003). Cette technique vise à rétablir les fonctions d'accumulation de tourbe et l'hydrologie du système en implantant un tapis de sphaignes comprenant plusieurs plantes typiques de bogs et en appliquant différentes actions pour remouiller le site. Elle consiste principalement à récolter une couche de sphaignes comprenant des plantes vasculaires et la banque de graines dans un bog naturel (site d'emprunt) et à épandre ce matériel dans le bog exploité qu'on veut restaurer. Le bog doit ensuite être remouillé grâce au blocage des canaux de drainage créés lors de la récolte pour permettre la croissance des sphaignes, qui nécessitent un niveau de nappe phréatique haut et stable (Gorham & Rochefort, 2003). Suite à la restauration écologique des tourbières exploitées, la composition en espèces qu'on y trouve devrait être semblable à celle des tourbières naturelles, l'accumulation de tourbe et le stockage de carbone devraient être à nouveau en fonction et la nappe phréatique devrait être stable et située environ 30 cm sous la surface de la tourbe (Gorham & Rochefort, 2003; Quinty & Rochefort, 2003).

Au Nouveau-Brunswick, l'extraction de la tourbe à des fins horticoles est une activité économique de premier plan (GNB, 2010). Dans la région de la péninsule acadienne, de nombreux bogs sont situés près de la côte (Figure 1).

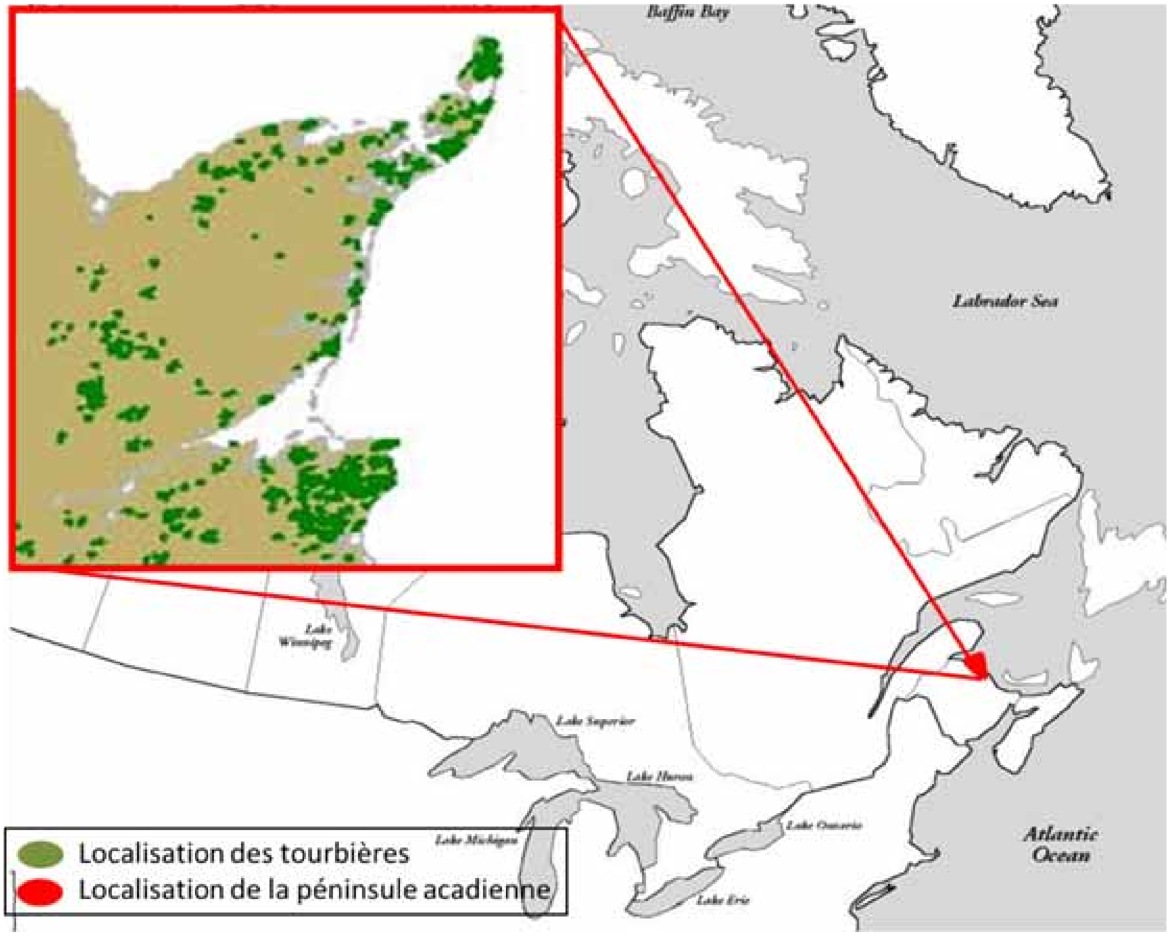

Figure 1 Les tourbières sont situées majoritairement près de la côte dans la région de la péninsule acadienne au Nouveau-Brunswick (GNB, 2013).

L’extraction de la tourbe abaisse la surface de la tourbière, ce qui contribue à augmenter les probabilités d’incursion de l’eau salée, conjointement avec les évènements de très hautes marées et de tempêtes (Mouneimne & Price, 2007; Breathnach, 2008). Suite à ces incursions d’eau salée, la récolte de la tourbe à des fins horticoles n’est plus envisageable et de grandes superficies de tourbières industrielles sont abandonnées. Étant donné la hausse prévue du niveau de la mer, plusieurs écosystèmes côtiers d’eau douce seront dans la même situation d’ici quelques années (Warrick & Oerlemans, 1990).

Effet de la salinité sur les végétaux

L'eau de mer est composée principalement de chlorure de sodium (NaCl). Les plantes vasculaires de milieux d'eau douce sont défavorisées par la salinité. Elles sont d'abord affectées par un stress hydrique car la forte concentration de NaCl dans le substrat entraine la sortie de l'eau des racines par osmose (Greenway & Munns, 1980). Leur croissance est ensuite réduite car les ions salins nuisent à l'absorption des éléments nutritifs. Puisque l'eau de mer renferme plus de sodium (Na^+) que de potassium (K^+), le Na^+ est absorbé préférentiellement au K^+ qui est un macronutriment impliqué dans l'activation enzymatique (Bernstein & Hayward, 1958; Wyn Jones & Gorham, 2004; Breathnach, 2008). Le chlore altère la synthèse de chlorophylle, provoque le jaunissement des feuilles et réduit la photosynthèse (Greenway & Munns, 1980). Le NaCl est aussi néfaste pour les sphaignes, car il s'incruste sur les feuilles des sphaignes par l'entremise du processus d'évapotranspiration. Cela brise les sphaignes en raison du poids élevé sur leurs feuilles et entraine le dessèchement des feuilles autour de la zone incrustée de sel, ce qui cause un taux de mortalité élevé, même à des salinités très faibles (Wilcox, 1984). De plus, le sel persiste longtemps dans la tourbe (Mouneimne & Price, 2007) et des inondations répétées sont susceptibles de se reproduire. Il n'est donc pas pertinent d'utiliser la technique de transfert muscinal (Rochefort, 2000). L'introduction d'eau salée dans le système empêche donc le rétablissement d'une végétation typique de bogs (Wilcox, 1984) et les sites peuvent demeurer dénudés durant plus d'une décennie (Annexe 1).

Effet de l'hypoxie racinaire sur les végétaux

En plus d'avoir à faire face à un niveau de salinité supérieur à la normale, les plantes recolonisant les tourbières doivent aussi composer avec un milieu déficient en oxygène. L'extraction de la tourbe abaisse le niveau de la surface des tourbières et les tourbières situées près du niveau de la mer sont souvent très humides. En effet, les entreprises exploitantes doivent souvent utiliser des pompes pour bien assécher les tourbières côtières en plus des canaux de drainage traditionnels et le pompage cesse en même temps que l'exploitation (Quinty, 2009). Un des défis pour la végétation est donc l'hypoxie racinaire.

Elle ralentit la croissance végétale car l'oxygène (O_2) qui agit comme accepteur d'électron, est peu soluble dans l'eau et y diffuse lentement. Lorsque l'O_2 est limitée, les transferts d'électrons et la respiration le sont aussi et c'est la fermentation qui a lieu mais en produisant moins d'énergie (Grable, 1966; Barrett-Lennard, 2003; Gibbs & Greenway, 2003).

Effet de la faible disponibilité des éléments nutritifs sur les plantes

En plus de ces défis liés à l'envahissement par l'eau de mer, le fait que le tout se déroule en tourbières cause aussi des problèmes d'acidité et de faible disponibilité des éléments nutritifs. Le pH acide et la constitution des bogs en font des milieux où les éléments nutritifs sont très peu disponibles pour les plantes. Un grand défi pour les plantes vasculaires des bogs est la carence en phosphore (P) (Ferland & Rochefort, 1997). Une carence en P affecte principalement les transporteurs d'énergie tels que l'Adénosine TriPhosphate (ATP) et donc la photosynthèse (Sa & Israel, 1991; Pieters *et al.* 2001). Les acides nucléiques, certains enzymes et les phospholipides en sont aussi affectés (Raven *et al.* 2003). De plus, puisque les bogs sont isolés des eaux de ruissellement enrichies en minéraux tels que calcium (Ca) et le magnésium (Mg), ces macroéléments pourraient aussi être des facteurs limitant la croissance de la végétation (Linthurst & Seneca, 1980; Andersen *et al.* 2011). Le Ca est une composante des parois cellulaires, un cofacteur d'enzymes et il intervient dans la perméabilité des membranes cellulaires (Raven *et al.* 2003). Le Mg est un constituant majeur des molécules de chlorophylle et un activateur enzymatique, sans lequel la chlorophylle ne peut être synthétisée (Raven *et al.* 2003).

Apports nutritifs potentiels

Afin de combler les besoins en phosphore (P) des plantes en bogs exploités, l'utilisation de roche phosphatée a été tentée avec succès dans les études de Ferland et Rochefort (1997) et de Sottocornola *et al.* (2007). L'ajout de phosphore dans les bogs abandonnés d'eau douce améliore l'établissement des plantes vasculaires et de bryophytes tels que *Polytrichum* *strictum*, qui agissent comme des plantes compagnes pour l'établissement de la sphaigne. En restauration de marais salés, la fertilisation de P est parfois utilisée, conjointement avec la fertilisation principale d'azote (N) (Zedler, 1984; Broome *et al.* 1988).

Pour satisfaire aux besoins en minéraux tels que le calcium (Ca) et le magnésium (Mg), l'utilisation de chaux dolomitique est envisagée. La chaux est parfois utilisée dans la restauration de marais salés acides. Dans l'étude de González-Alcaraz *et al.* (2011) qui visait à restaurer des marais salés acides contaminés par des déchets miniers, l'application d'un mélange de calcite et de dolomite a permis d'améliorer les conditions du substrat en augmentant le pH du sol, en augmentant la disponibilité des éléments nutritifs essentiels, en atténuant celle des métaux lourds toxiques et en améliorant la structure et la conductivité hydraulique du sol. En restauration de fens, la chaux a aussi été testée dans une étude de Beltman *et al.* (2001) visant le retour d'une végétation typique de fens riches et basiques où l'acidification a permis à des espèces plus compétitives de s'implanter. Le traitement de chaux visant l'augmentation du pH n'a été efficace que lorsqu'il était combiné avec la suppression de la végétation indésirable et avec une amélioration de l'hydrologie par la création de canaux de drainage.

Végétation potentielle

Spartina pectinata Link. et *Carex paleacea* Schreb. ex Wahlenb. sont des espèces de marais salés qui ont été réintroduites en bogs exploités contaminés par le sel lors d'études antérieures et semblaient prometteuses, malgré qu'elles ne se soient pas suffisamment étendues pour dépasser les limites des parcelles où elles avaient été plantées (Montemayor, 2006; Breathnach, 2008). Dans l'étude de Breathnach (2008), il est recommandé d'utiliser la technique de transfert de foin, récolté dans une portion du mi-marais dominé par *S. pectinata.* Cette méthode consiste à faucher et récolter les portions aériennes de la végétation et à étendre ce matériel dans le bog contaminé par le sel. De la roche phosphatée a aussi été appliquée (25 g m^{-2}), sans améliorer significativement les couverts de végétation. Par ailleurs, il a été relevé que de la roche phosphatée avait été déversée par erreur dans une mare, dont la périphérie a par la suite été recouverte de végétation. Montemayor (2006) a quant à elle découvert que *S. pectinata* pouvait s'implanter à divers niveaux au-dessus de la nappe phréatique dans le bog contaminé par le sel, malgré le pH, l'hypoxie racinaire et la salinité, tandis que *J. balticus* Will. était mieux adapté aux surfaces de tourbe à nu plus au sec (éloignées de la nappe phréatique). D'autres observations ont aussi été faites dans des parcelles expérimentales où *C. paleacea* avait été transplantée et cette espèce montrait une croissance prometteuse. En se basant sur ces observations, *S. pectinata* et *C. paleacea* sont donc des choix pertinents pour la ré-végétalisation des bogs contaminés par l'eau salée.

Spartina pectinata et *Carex paleacea* croissent naturellement dans le haut-marais salé qui est aussi indépendant des marées quotidiennes. Le genre *Spartina* est souvent transplanté et semé en restauration des marais salés car il est un colonisateur majeur et qu'il constitue un habitat favorable pour la faune sauvage (Zedler, 1984; Broome *et al.*, 1988). *C. paleacea* est membre de la section *Phagocytys* de la famille des *Cypéracées,* qui sont aussi présents dans les bogs (Bruederle & Fairbrothers, 1986; Broome *et al.* 1988). Ces espèces se trouvent dans les marais, mais ne sont pas des halophytes obligées (Barbour, 1970; Waisel, 1972). Elles pourraient donc proliférer aussi en sols moins salés.

Les marais salés sont les écosystèmes naturels les plus similaires aux bogs exploités contaminés par le sel dans la région. Il est donc pertinent de s'intéresser aux techniques de restauration de ces écosystèmes afin de voir s'il est possible de transposer ces méthodes à nos bogs. La restauration des marais salés comporte plusieurs aspects. Habituellement, la topographie de la côte doit être remodelée afin de retrouver une pente et une hauteur adéquate (Broome *et al.* 1988; Weishar *et al.* 2005). Le remodelage de la topographie doit aussi tenir compte de l'influence de la marée sur la zonation des plantes (Darnell & Smith, 2001). Dans les bogs à l'étude, en revanche, des murs de tourbe ont été érigés entre les bogs et la mer de manière à amoindrir les futures entrées d'eau salée. Ces immenses murs seraient très difficiles à détruire et la zone côtière adjacente est utilisée pour la cueillette de bivalves par les locaux. En conséquence, le déversement de tourbe dans la zone côtière qui serait engendré par la destruction des murs n'est pas souhaitable et cette étude ne considérera pas l'influence des marées et la topographie. La transplantation et l'ensemencement d'espèces végétales appropriées est ensuite effectuée principalement par transplantation (ex : *Spartina sp* et *Salicornia sp*.) tout en favorisant les espèces halophytes à celles d'eau saumâtre (Zedler, 1984; Konisky *et al.* 2006). Afin d'obtenir une croissance rapide pour avoir une bonne biomasse lorsque des tempêtes, des sécheresses ou d'autres évènements néfastes pour la végétation surviendront, une fertilisation principalement azotée (N) est appliquée directement dans les trous de plantation ou en bandes (Broome *et al.* 1988). Les mélanges de fertilisants peuvent varier et inclure aussi du P et du potassium (K), ou seulement de l'N et du P, mais l'élément principal de la fertilisation en marais salés est l'N, qui y est l'élément le plus limitant pour la croissance de la végétation (Squiers & Good, 1974; Cargill & Jefferies, 1984; Broome *et al.* 1988).

Il existe tout de même des différences majeures entre le régime nutritif des bogs contaminés par l'eau salée et de marais salés. La disponibilité des éléments nutritifs des bogs naturels est très faible, même en tenant compte de l'introduction d'eau de mer (Montemayor *et al.* 2010; Andersen *et al.* 2011). Les minéraux présents normalement dans le sol tels que le calcium et le magnésium, ou ceux normalement présents dans l'eau de ruissellement tels que le phosphore y sont rares (Ryden *et al.* 1973; Andersen *et al.* 2011). Le pH acide des bogs nuit aussi à la disponibilité des éléments nutritifs, qui est supérieure près de la neutralité (Brady & Weil, 2003). La salinité des bogs exploités contaminés par le sel est en moyenne plus faible que celle des marais salés (Breathnach, 2008). La plupart des plantes qui se trouvent dans les marais salés peuvent aussi vivre en milieux d'eau douce, ainsi cette différence ne devrait pas être capitale (Barbour, 1970; Waisel, 1972). Dans le but d'atténuer les différences dans la disponibilité des éléments nutritifs, des fertilisants pourraient être utilisés.

Hypothèses et objectifs

Il est crucial de trouver une nouvelle approche pour végétaliser efficacement les bogs contaminés par l'eau salée. Nous émettons l'hypothèse que la végétation du haut-marais salé devrait pouvoir tolérer les conditions de salinité, d'hypoxie racinaire et de pH acide. Une fertilisation de phosphore ainsi qu'un amendement de chaux devrait améliorer la croissance de la végétation en rendant disponibles les éléments nutritifs manquants. L'objectif de cette étude est d'encourager la colonisation végétale de deux bogs exploités contaminés par le sel dans des zones côtières de l'est de l'Amérique du Nord.

Chapitre 2: Acceleration of plant colonization in salt contaminated cutover bogs, using salt marshes vegetation introduction and amendments

Résumé

Les bogs côtiers peuvent être envahis par l'eau de mer suivant l'extraction de la tourbe qui abaisse leur surface. Lorsqu'inondés, ils demeurent sans couvert végétal en raison des conditions salines et acides, de la nappe phréatique élevée et de la faible disponibilité des éléments nutritifs. Nous pensons que les plantes de marais salés devraient survivre en bogs exploités contaminés par le sel, avec les amendements adéquats. L'objectif est d'accélérer la colonisation végétale de ces bogs. Une expérience terrain testant l'établissement de plantes de marais salés dans deux de ces bogs visait à déterminer si la roche phosphatée (P_2O_5) améliore la disponibilité du P et si la chaux dolomitique (CaO.MgO) améliore la disponibilité du Ca et Mg, mais aussi celle d'autres macronutriments *via* une hausse du pH. Cinq matériaux végétaux étaient testés : (1) la transplantation de *Carex paleacea* et de (2) *Spartina pectinata*, (3) le transfert de diaspores de marais salés en juillet et (4) en août et (5) un témoin. Deux doses de chaux (0 ou 100 g m^{-2}) et de P (0 ou 50 g m^{-2}) étaient combinées aux matériaux végétaux. Une expérience complémentaire en serre visait à déterminer la dose adéquate de chaux en appliquant trois doses (0, 2.5 and 7.5 kg m^{-3}) à des transplants et semences de *C. paleacea* et *S. pectinata.*

La roche phosphatée a amélioré la croissance de tous les matériaux végétaux, effet détectable par le ratio N:P optimal. La transplantation de *C. paleacea* a entraîné les couverts végétaux et les biomasses aériennes les plus élevés et le transfert de diaspores de marais salés a entraîné une diversité d'espèce supérieure malgré l'établissement plus lent du couvert végétal, tandis que la chaux n'a pas amélioré la croissance de la végétation.

Afin d'accélérer la colonisation végétale des bogs exploités et contaminés par l'eau de mer, on recommande donc l'application de roche phosphatée, la transplantation de *C. paleacea* et le transfert de diaspores de marais salés.

Abstract

Coastal bogs are prone to sea water contamination following peat harvest that lowers the peat surface. Hereafter, they remain mostly covered by bare peat during decades because of salinity, low pH, high water table level and low nutrient availability, mostly P, Ca and Mg. We hypothesize that salt marsh communities should proliferate in salt contaminated cutover bogs in combination with adequate amendments. The goal of this study is to accelerate plant colonization of those bogs. A field experiment testing the establishment of salt marsh plants on sodic peat aimed to examine whether rock phosphate fertilizer (P_2O_5) improve P availability and whether dolomitic lime (CaO.MgO) improve Ca and Mg availability, but also N, P and K *via* a pH upgrade. Five plants material treatments were evaluated: (1) the transplantation of *Carex paleacea* and (2) *Spartina pectinata*, (3) salt marsh diaspores transfer of July and (4) August and (5) a control. Two lime doses (0 or 100 g m^{-2}) and P doses (0 or 50 g m^{-2}) were combined to plant materials. A complementary greenhouse experiment aimed to define the adequate lime dose needed by applying three lime doses (0, 2.5 and 7.5 kg m^{-3}) to transplants and seeds of *C. paleacea* and *S. pectinata*.

Rock phosphate fertilizer resulted in better growth of all plant materials and that effect was also detected through the optimal N:P ratio in leaves (Meuleman, 2010). Transplantation of *C. paleacea* resulted in higher plant cover and aerial biomass than all other plant materials and salt marsh diaspores transfer led to higher species diversity, even if plant cover was low to develop. Lime was never associated to plants growth improvement.

To promote plant recolonization of salt contaminated cutover bogs, adding P is an asset. *C. paleacea* is a good species to transplant, in combination with the transfer of salt marsh diaspores.

Introduction

In New Brunswick (Eastern Canada), peat exploitation is a leading economic activity and producers are required to restore peatlands after peat extraction (GNB, 2010). Normally, a moss layer transfer technique elaborated by the Peatland Ecology Research Group (PERG) is used to ecologically restore peat extracted bogs (ombrotrophic peatlands). This technique aims to restore the peat accumulation functions by focusing on the implantation of a *Sphagnum* carpet and a large fraction of the former biodiversity of typical bog transported with the moss layer (Ferland & Rochefort, 1997; Quinty & Rochefort, 2003). It consists mainly in collecting the moss layer including vascular plants in a natural bog (donor site) than to spread it in the former peat extracted bog to restore. The drained bog must be rewetted by blocking drainage channels to allow *Sphagnum* growth which requires a high and stable water table level (Quinty & Rochefort, 2003).

Coastal bogs are prone to invasion by sea water because of the lowering of ground level resulting from the extraction of peat. Bogs facing salt contamination are unlikely to spontaneously recover a typical bog vegetation (Wilcox 1984), consequently leaving peat landscapes denuded for more than a decade (Annexe 1). *Sphagnum* mosses do not thrive in such bogs because of the difficulty in performing vital exchanges with the environment, even at low salt concentration (Clymo 1963; Wilcox, 1984). Concerning vascular plants, a combination of various factors lead to a low plants establishment in salt contaminated cutover bogs. Constraints to their establishment and growth are mainly the salinity (Bernstein & Hayward, 1958; Greenway & Munns, 1980; Wyn Jones & Gorham, 2004; Breathnach, 2008), combined with an acid pH and high water table level (Grable, 1966; Barrett-Lennard, 2003; Gibbs & Greenway, 2003), and low nutrient availability, mainly phosphorus (P) (Sottocornola *et al.* 2007; Breathnach, 2008; Andersen *et al.* 2011), calcium (Ca) and magnesium (Mg) (Raven *et al.* 2003; Andersen *et al.* 2011). From previous studies, *Spartina pectinata* Limk. and *Carex paleacea* Schreb. ex Wahlenb. transplantation was tested in salt contaminated cutover bogs and seems to be promising even if the plants did not proliferate out of the area of introduction (Montemayor, 2006; Breathnach, 2008). Breathnach (2008) recommended the use of the hay transfer method to collect *S. pectinata* seeds of mid-salt marsh. This method consists into collecting aerial parts of vegetation using a scythe once seeds are matures and to spread it onto the bog. Rock phosphate (25 g m^{-2}) was also applied but it did not improve significantly groundcovers. However, a drop of unknown amount of rock phosphate in a pond resulted in a high plant cover around it (Breathnach 2011, personal communications). Montemayor (2006) showed that *S. pectinata* could survive at all ground elevations, including in the waterlogged and salty harsh conditions found at lower elevations. Our observations of experimental plots containing *C. paleacea* in a severely salt affected area of a cutover bog showed that this species was also growing well. According to these studies, *S. pectinata* and *C. paleacea* are relevant choices to pursue testing of re-vegetation of salt contaminated cutover bogs.

Salt marshes are regionally the most similar natural ecosystem to salt contaminated cutover bogs. Particularly, the upper marsh is independent of daily flood tides, as are our bogs. *Spartina pectinata* and *Carex paleacea* are found in abundance in this zonation of salt marshes. *Spartina* gender is often used in salt marsh restoration because it is a strong colonizer and *C. paleacea,* also found in bogs (Bruederle & Fairbrothers, 1986; Broome *et al.* 1988). Restoration of salt marshes is usually done by remodelling the coastal topography, transplanting appropriate halophyte plants and seedlings (i.e. : *Spartina sp* and *Salicornia sp*.) and by applying nitrogen (N) fertilization in the planting hole when required (Squiers & Good, 1974; Cargill & Jefferies, 1984; Zedler, 1984; Broome *et al.* 1988; Weishar *et al.* 2005; Konisky *et al.* 2006). Yet there are substantial differences between nutrient regimes of salt marshes and bogs. The availability of nutrients in natural bogs is very low, even with sea water introduction (Montemayor *et al.* 2010; Andersen *et al.* 2011) while salt marshes are richer (Valiela *et al.* 1978; Craft *et al.* 1999; Deegan *et al.* 2007). Bogs are peatlands that have accumulated a sufficient thickness of peat to rise above the adjacent lands around. Consequently, they do not receive runoff from de mineral ground, only atmospheric precipitations and depositions. Minerals normally found in the soil such as Ca and Mg and in ground runoff, as P, are thus rare (Ryden *et al.* 1973; Quinty &

Rochefort, 2003; Andersen *et al.* 2011). Bog's acid pH also reduces nutrients availability, which in soil is usually best towards neutrality (Brady & Weil, 2003). Salinity found in salt contaminated cutover bogs is on average, lower than that of salt marshes. Most of salt marsh plants can also grow in freshwater habitats when the space is not completely cover by other plants (Barbour, 1970; Waisel, 1972). In order to mitigate these differences in nutrients availability, fertilizers could be used.

It is important to find a new approach to re-vegetate efficiently salt contaminated cutover bogs because the phenomena will be soon amplified with climate change and sea level rise (Warrick & Oerlemans, 1990). The objective of this study is to encourage plant colonization of two such bogs. Phosphorus fertilizer and lime amendment should both improve vegetation growth and spatial colonisation by improving nutrients availability while salt marsh vegetation should survive, grow and germinate in salt contaminated cutover bogs.

Materials and Methods

Study sites

The field experiment took place in Pokesudie and Shippagan bogs, situated in north-eastern New Brunswick, Canada (47°49’N; 64°49’W and 47°41’N; 64°46’W). These peatlands have been peat extracted during several years for the valued horticultural peat quality using a vacuum method. This method consists in suppressing the top layer of vegetation, thus removing the seeds bank and subsequently draining the bog with ditches every 30 meters (CSPMA, 2010). Peat extracting ceased following invasion by sea water that occurred during a storm surge in January 2000 for northern Pokesudie site and in eastern Shippagan site (Figure 2). The latter bog still continues to receive small punctual sea water intrusions during storm event or high tides. Berms and ditches were built around both bogs to prevent further invasion by sea water but failed in the eastern Shippagan site.

Figure 2 Description of the study sites. Pokesudie bog (left) and Shippagan bog (right), situated in the Acadian peninsula of New Brunswick.

Following salt water invasion in the two bogs, drainage ditches collapsed naturally and water table remained near or at the surface during the good parts of the growing seasons.

Plant colonisation on those sites is slow and, more than ten years after salt invasion, bare peat still dominates the surface. The peat near the surface is fibric (Von Post 2 and 3) due to the premature cessation of the extraction. Only a few plants from *Juncus*, *Carex*, *Eriophorum* and *Scirpus* genders are sparsely present.

Field experiment

Experimental design

To test the establishment of local marsh plants onto salt contaminated cutover bogs, a field experiment was designed as a factorial design comprising four blocks and three factors: 1. plant material introduced (5 types) 2. liming treatment (+/-) and 3. phosphorus fertilization (+/-) treatment. The 9 m^2 plots were spaced with a minimum of five meters to the next experimental unit to prevent amendments migration due to high water table level. Dead wood and any plants that were initially present at the surface of the plots were first removed.

Plant material

The plant materials were: 1) plantation of *S. pectinata*, 2) plantation of *C. paleacea,* 3) diaspore transfer of salt marsh layer in July, 4) diaspore transfer of salt marsh layer in August and 5) a bare peat control.

The donor sites were the natural salt marshes located next to each bog, to ensure that the vegetation was adapted to regional ecological conditions. Most important environmental differences between those salt marshes and bogs were the higher pH, salinity and nutrient availability of the salt marshes (Table 1). The field experiment took place over two growing seasons and within the sections most severely affected by seawater (Surrounded by dotted lines on Figure 2). Growing season of 2011 was wet (621 mm ± 19) while 2012 (461 mm ± 11) was closer to historical standards (412 ± 18) according to Caraquet (47°48'00.000°N;

64°52’00.000”O) and Bas Caraquet (47°48’08.000°N; 64°50’00.000”O) stations (Environnement Canada, 2013).

Table 1 Soil environmental conditions in Pokesudie and Shippagan peatlands salty sections and salt marshes (donor sites) (mean ± SE).

Environmental conditions	Northern Pokesudie bog	North-Eastern Shippagan bog	Pokesudie salt marsh	Shippagan salt marsh
Salinity (‰)	0.48 (0.03)	1.39 (0.07)	7.03 (1.06)	7.63 (0.87)
pH	3.6 (0.0)	3.5 (0.0)	5.7 (3.0)	5.2 (0.1)
Redox (mV)	173 (6)	143 (8)	41 (32)	55 (36)
Water table level (cm)	-7.2 (1.0)	-4.8 (0.6)	-9.4 (1.3)	-11.2 (3.2)
[P] (mg g^{-1})	0.011 (0.0002)	0.0006 (0.0002)	0.081 (0.0009)	0.021 (0.0003)
[Ca] (mg g^{-1})	1.434 (0.087)	1.505 (0.074)	2.228 (0.837)	0.657 (0.286)
[Mg] (mg g^{-1})	1.747 (0.099)	2.996 (0.207)	5.288 (1.517)	1.261 (0.237)

Elevation of both sites above sea level was between 0 to 2 meters.

For individual species introduction, 49 uniform plugs of five cm diameter (rhizome and soil) of *Carex paleacea* and *Spartina pectinata* were collected from the salt marsh and transplanted at the end of June 2011 (Annexe 2) in each plot including the buffer zone. Salt marsh diaspores transfer is a new approach based on the moss layer transfer. It consists in collecting the aerial and underground parts of vegetation (including the seeds bank) using a rototiller than to spread it on the salt contaminated cutover bog. These diaspores were collected and spread at mid-July and mid-August 2011 (Annexe 3). Plant material collected in 1 m^2 of the salt marsh was spread over 6 m^2 in bog plots; then the surface was flattened to ensure good contact with humid peat.

Liming and phosphorus fertilization treatments

To facilitate acclimation of the vegetation to bog acidic and organic conditions, dolomitic lime ($CaCO_3 \cdot MgCO_3$) amendment and rock phosphate fertilizer (H_2PO_5) were tested. Lime was used to provide Ca and Mg and to raise pH while rock phosphate was used to provide P. In the transplantation plots of *Carex paleacea* and *Spartina pectinata* and the control plots (with no plant material), lime (18 g or 0 g) or rock phosphate (9 g or 0 g) was added in the planting holes. In the marsh diaspore transfer technique, lime (100 g m^{-2} or 0 g m^{-2}) or rock phosphate (50 g m^{-2} or 0 g m^{-2}) was spread at the surface of the plots and incorporated to the peat with a rake (Quinty & Rochefort, 2003; Sottocornola *et al.* 2007; N. Mattson, Cornell university, pers. comm. for the amount of lime to be added; CRAAQ, 2010).

Monitoring

All monitored variables were taken in a 2 x 2 m quadrat centered within the 9 m2 experimental unit. Abiotic (pH, salinity, redox, water table level) and biotic (height and percent cover) data were recorded in mid-July 2012 among the 80 experimental units. *Spartina pectinata* (very abundant) and *Spartina alterniflora* (scarce) were recorded as *Spartina sp.* because inflorescences were not always present; in absence of flowers the two species are difficult to tell apart. Aerial and underground biomasses were collected in August 2012 in each plot (after two growing seasons for transplants and 1.5 growing season for marsh diaspore transfer). Aerial biomass was collected in a 50 x 50 cm subplot and underground biomass in a 25 cm x 25 cm subplot, both located in the middle of the plots. Aerial biomass was sorted to separate spontaneous vegetation from salt marsh plant introduction; no sorting by plant groups was done for underground biomass. Biomass samples were dried at 70° C during three days, and then weighed. Leaf samples were collected at the end of the second growing season, but before leaf senescence, for chemical analyses. Peat samples were collected in July 2012 (after 1.5 growing season for transplants and 1 season for marsh diaspora transfer) in each plot of all blocks and in donor sites for chemical analyses. Digestion of foliar and peat tissues was done with the wet oxidation procedure of Parkinson and Allen (1975). Exchangeable nutrients were extracted using NH_4Cl-$BaCl_2$ 0.1M (Amacher et al. 1990), P was extracted using P Bray II (Bray & Kurtz, 1945) with Quickem method 12-115-01-1A whereas total N was extracted using Quickem method 13-107-06-2D. Analyses were done using a Quickem 4000 (Lachat Instrument, Milwake, WI, USA).

Greenhouse experiment

Experimental design

To precise lime doses that can improve salt marsh transplants growth and germination, a greenhouse experiment comprising five complete blocks has been carried out. Two plant species (*Carex paleacea* and *Spartina pectinata*) were tested in combination with three concentrations of dolomitic lime (0, 2.5 and 7.5 kg m^{-3}) for a total of six experimental units per block (Annexe 4). Each container was filled with 8 cm of horticultural sand at the bottom and sodic peat (i.e. peat that has been contaminated with salt water) collected in Shippagan bog on the top 20 cm. Because Shippagan bog is little affected by salinity (1.2 ‰) and to expand the range of salinity tested, greenhouse experiment peat (1.1 ‰) was therefore mixed with salt (NaCl) in the containers before adding the plant materials to reach a salinity of 2.5 ‰. The watering was done using rainwater every two or three days at the beginning of the experiment and was spaced when experiment was progressing to mimic water table levels measured in field experiment throughout the 2011 growing season.

Plant material

Transplants and seeds were collected at the beginning of October 2011 in Shippagan salt marsh. Plugs were stored at 4 °C with humid peat, in the dark for three months, to break dormancy. Seeds were stored in the same conditions, but they were transferred in jars of brackish water (16 ‰ for *S. pectinata* and 8 ‰ for *C. paleacea*) two weeks before the beginning of the experiment to break dormancy and improve germination rate (Van Der Valk, *et al.* 1999; Wijte & Gallagher, 1996a). At that time, lemma and palea of *S. pectinata* seeds and scales of *C. paleacea* seeds were removed by hands (Stalter, 1972; Walsh, 1990). Six plants were transplanted along with two groups of 50 seeds in each experimental unit. Groups of seeds were surrounded by a plastic border 5 cm high and 10 cm in diameter to prevent seed from dispersing in the containers during watering.

Liming treatments

Dolomitic lime was added in three concentrations (0, 2.5 and 7.5 kg/m^3). Lime was incorporated into the peat two months and a half before the beginning of the experiment. Peat was regularly mixed and pH was measured every two weeks until the pH stabilized at respectively 3.76 ± 0.04, 4.70 ± 0.13 and 6.22 ± 0.09.

Monitoring

Transplants were grown during four months while seed germination was followed during two months. Soil characteristics (salinity, pH and redox) and biotic data (height and number of germinated seeds) were recorded once at the end of the experiment. Concerning transplants, peat and leaf samples were also collected in each container for three chosen representative blocks of the five blocks for chemical analysis. All aerial biomass was collected in each container but underground biomass was collected in two quarters of the container, randomly chosen. Plant material was dried at 70° C during three days and then weighed. Chemical analyses were done using the same techniques as described for the field experiment.

Data analyses

In field experiment, biomass and cover of the different plant materials were compared with each other. Concerning greenhouse experiment, due to major differences in *S. pectinata* and *C. paleacea* morphology, data from the transplants were analysed separately for the two species. However, their seed germination rates were compared across treatments.

Data of the factorial designs were compared using the MIXED procedure of SAS (Statistical system software 9.3, SAS Institute Inc., Cary, U.S.A.) for both experiments. Normality and homogeneity of variance were tested and variance was modeled with GROUP statement of the function REPEATED when homogeneity was not respected. Degrees of freedom were adjusted accordingly. Significant differences between treatments were determined using least-square means (LS means). Aikaike Information Criterion (AIC) was used to determine best models while Shapiro-Wilk and Kolmogorov-Smirnov were used to verify normality assumption.

Results

Field experiment

Phosphorous fertilizer had the greatest positive effect on vegetation establishment, for the introduced transplants and diaspores transfer treatments. Spontaneous (P treatment F = 4.8; P = 0.040), introduced (P treatment F = 7.5; P = 0.008) and total (P treatment F = 8.7; P = 0.010) vegetation aerial biomass and spontaneous (P treatrment F = 10.8; P = 0.003) and total (P treatment F = 21; P < 0.001) vegetation covers also almost doubles with P fertilization while *S. pectinata* (P treatment F = 7.2; P = 0.026) and *C. paleacea* (P treatment F = 8.6; P = 0.017) heights increased by 132 % and 116 % (Table 2; Annexe 5; Annexe 6).

Table 2 Positive effect of rock phosphate (P) addition on plant's heights, aerial biomass and vegetation covers (mean ± SE). Only significant differences are listed. N for height = 40 and n for aerial biomass and covers = 80.

Plant's response	With Phosphorus	Without Phosphorus
Spartina pectinata height (cm)	25 (8)	19 (7)
Carex paleacea height (cm)	36 (1)	31 (3)
Spontaneous vegetation aerial biomass (g m^{-2})	116 (20)	62 (11)
Introduced vegetation aerial biomass (g m^{-2})	45 (11)	23 (7)
Total aerial biomass (g m^{-2})	161 (13)	86 (23)
Spontaneous vegetation cover (%)	19 (3)	11 (2)
Total vegetation cover (%)	25 (3)	13 (2)

When *C. paleacea* transplants received rock phosphate amendment, vegetation cover was twice that in absence of P amendment (interaction of introduced vegetation treatment by P treatment F = 3.7; P = 0.019) and it produced in general more cover than all other plant material treatments (interaction of introduced vegetation treatment by P treatment F = 46; P < 0.001) (Figure 3; Annexe 5). As expected, control plots still had the lowest cover two years after the plant material introduction treatments took place. In general, P was well assimilated by plants, as shown by 160 % higher P concentration in plant tissue (1.56 ± 0.15 vs. 0.96 ± 0.16 mg g dry mass^{-1}; P treatment F = 19; P = 0.001) and lower N:P ratio (14.5 ± 1.4 vs. 24.7 ± 1.7; F = 20; P = 0.004) in leaves of plants that received P amendment (

Annexe 7). Underground biomass was not influenced by P additions (P treatment F = 1.9; P = 0.177) (Annexe 6).

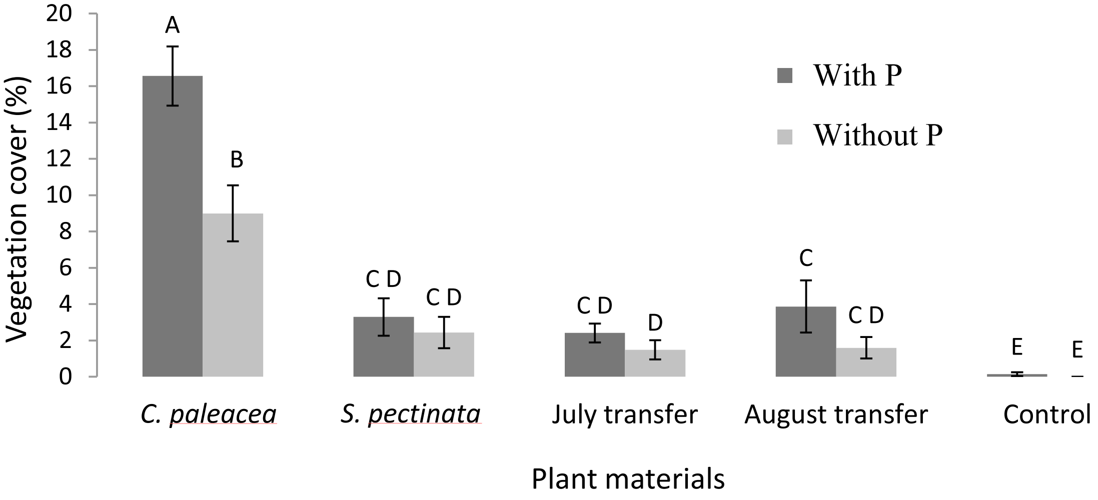

Figure 3 Introduced vegetation cover according to the type of plant material from salt marshes and the addition of phosphorus fertilizer (mean ± SE). *Carex paleacea* and *Spartina pectinata* were transplanted at the beginning of July 2011 while salt marsh diaspores were spread in mid-July and mid-August 2011. Plant cover was recorded in mid-summer 2012. Different capital letters indicate significant differences between treatments following protected LSD. (F = 3.7 and P = 0.019 for the interaction Veg*P).

Addition of lime increased peat pH from 3.5 (± 0.1) to 3.8 (± 0.1) (lime treatment F = 8.9; P = 0.004) and doubled Ca concentration in peat (1.8 ± 0.2 *vs* 3.7 ± 0.7 mg g^{-1} with lime; lime treatment F = 6.5; P = 0.025) (Annexe 8). Lime was also well assimilated by plants, as shown by the 170 % higher Ca concentration in leaves of plants that received lime treatments compared to those that did not receive any (1.61 ± 0.38 *vs* 2.69 ± 0.39 mg g^{-1} with lime; lime treatment F = 6.4; P = 0.022) (

Annexe 7). This was related to higher foliar Ca:Mg ratios in limed plots than in plots with no addition of lime (lime treatment F = 9.1; P = 0.007). However, introduced aerial biomass tended to be lower when lime was added (42 ± 12 g m^{-2} without lime *vs* 26 ± 7 g m^{-2} with lime; lime treatment F = 4.3; P = 0.043) (Annexe 6). Transplantation of *Carex paleacea*, all fertilizer treatments confounded, showed the greatest introduced aerial biomass of all plant introduction treatments (introduced vegetation treatment F = 30.9; P < 0.01) (Annexe 6; Figure 4). Inversely, marsh layer diaspores transfers and control led to more aerial biomass of spontaneous vegetation than in the transplantation treatments (introduced vegetation treatment F = 3.5; P = 0.026) (Annexe 6; Figure 4). As a result, total aerial biomass, combining spontaneous and introduced vegetation, was not significantly affected by the introduced plant material (introduced vegetation treatment F = 0.8; P = 0.596) (Annexe 6). The same trend was observed with respect to vegetation covers (data not shown).

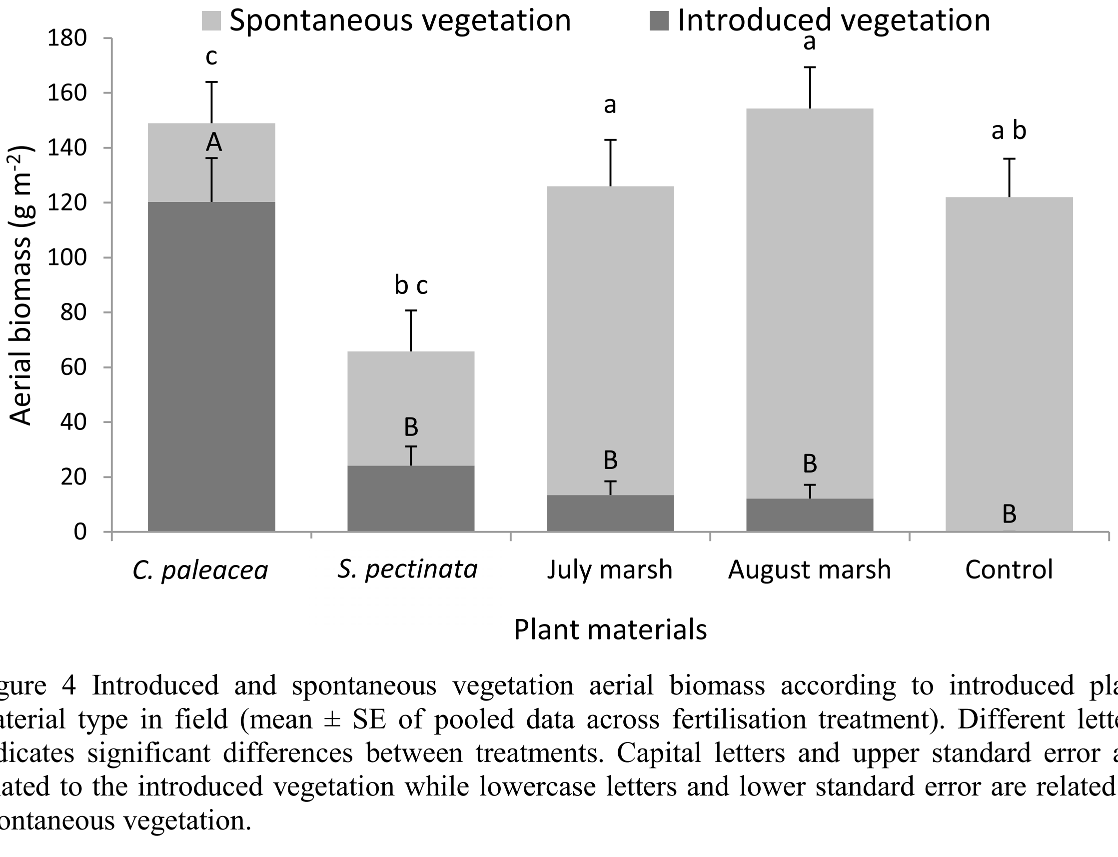

Figure 4 Introduced and spontaneous vegetation aerial biomass according to introduced plant material type in field (mean ± SE of pooled data across fertilisation treatment). Different letters indicates significant differences between treatments. Capital letters and upper standard error are related to the introduced vegetation while lowercase letters and lower standard error are related to spontaneous vegetation.

Very few other plant species were found in *Carex paleacea* and *Spartina pectinata* transplantation plots (data not shown). Salt marsh diaspores transfers led to considerably more species richness. From the 15 species recorded in the natural salt marshes plots (donor sites), 11 successfully established once transferred in salt contaminated cutover bogs plots after two growing seasons (Table 3). *L. maritima, J. gerardii, J. balticus, C. paleacea, Spartina sp* and *S. sempervirens* were dominant in natural salt marsh one year after salt marsh diaspores collection, and they remained dominant in the bogs salt marsh transfer plots, except for *S. sempervirens*. However, their cover after two years of growth in the introduction sites was much lower than in the natural donor sites. *J. bufonius*, a spontaneous species which was strongly dominating bogs plots.

Table 3 Plant species diversity found in natural salt marshes (15 species) one year after salt marsh diaspores were collected was higher than in the plots where the layers were spread (11 species). Species are listed in descending order of cover in bog marsh transfer plots (mean ± SE).

Plant species	Cover (%)	
	Bog marsh transfer plots (introduction site)	Natural salt marshes (donor site)
Lysimachia maritima (L.) Gal., Banf. & Sold.	2 ± 1	11 ± 2
Juncus gerardii Loisel.	2 ± 0.5	21 ± 2
Juncus balticus Willd.	2 ± 0.5	5 ± 2
Carex paleacea Shreb. Ex Wahl.	2 ± 0.5	5 ± 1
Triglochin maritima L.	1 ± 0.5	4 ± 1
Plantago maritima L.	1 ± 0.5	4 ± 1
Potentilla anserina L.	1 ± 0.5	0.5 ± 0
Spartina sp.	1 ± 0.5	14 ± 2
Halerpestes cymbalaria (Pursh) Greene	1 ± 0.5	2 ± 0.5
Atriplex prostata Boucher ex de Candolle	0.5 ± 0	1 ± 0.5
Festuca rubra L.	0.5 ± 0	1 ± 0
Limonium carolinianum (Walter) Britton		3 ± 1
Salicornia depressa Stanley		3 ± 0.5
Carex Mackenziei Krecz.		4 ± 0
Solidago sempervirens L.		10 ± 0
Juncus bufonius L.**	21 ± 4	
Eriophorum angustifolium Honck.**	0.5 ± 0	

** Spontaneous vegetation

Greenhouse experiment

The liming greenhouse experiment showed significant effects of lime addition on germination of *Spartina pectinata* seeds (lime treatment F = 8.2; P = 0.006) and on growth of transplants of *Carex paleacea* (lime treatment F = 11; P = 0.017) and *S. pectinata* (lime treatment F = 4.5; P = 0.035) (Annexe 9). The intermediate dose (2.5 kg m^{-3} of dolomitic lime) led to the development of higher *S. pectinata* shoots (9.4 ± 0.39 cm) than with 7.5 kg m^{-3} of lime (8.2 ± 0.30 cm) or 0 kg m^{-3} (7.7 ± 0.18 cm). *Carex paleacea*'s height (lime treatment F = 6.0; P = 0.025) and aerial biomass (lime treatment F = 11; P = 0.017) and *S. pectinata*'s aerial (lime treatment F = 4.5; P = 0.035) and total biomass (lime treatment F = 28; P = 0.003) decreased significantly as the dose of dolomitic lime added increased (Figure 5). Germination rates of *S. pectinata* (24 ± 2.2 %) were five times greater than that of *C. paleacea* (5.1 ± 0.5 %), but no significant effect of lime addition was observed in either species (Annexe 9).

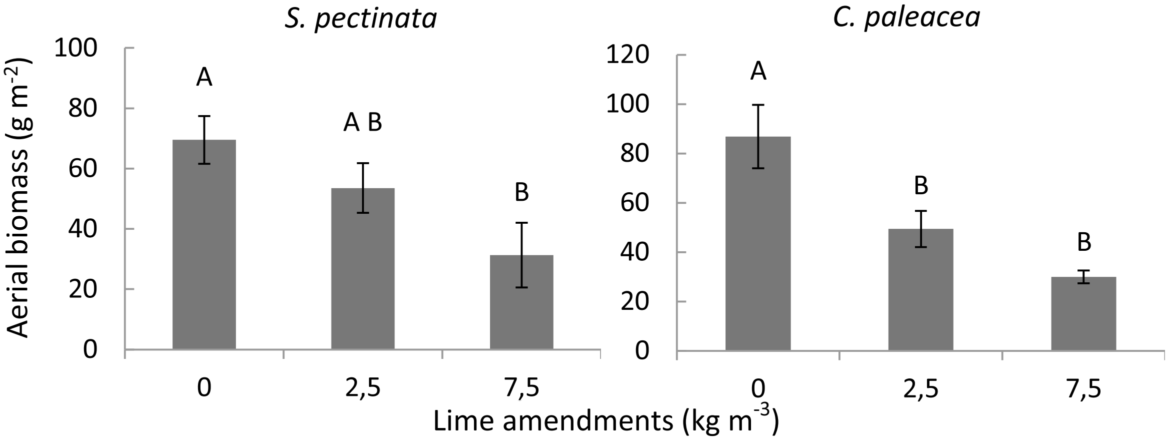

Figure 5 Dolomitic lime treatments significantly reduced *Spartina pectinata* and *Carex paleacea* aerial biomass (mean ± SE) (n=15). Different letters indicate significant differences following protected LSD.

Lime amendments increased the pH of the peat as predicted (lime treatment F > 296; P < 0.001), but also reduced the redox potential (Eh) in root zone (lime treatment F > 13; P < 0.003) (Figure 6; Annexe 9). Lime also succeeded to increase peat exchangeable Ca (lime treatment F > 69; P < 0.002) and Mg (lime treatment F > 88; P < 0.005) concentration while decreasing that of extractable Al (lime treatment F > 23; P < 0.002). At the same time, Mn and Fe concentrations in peat fell by 40 % (lime treatment F > 9.7; P < 0.029) for *C. paleacea* and 98 % (lime treatment F > 8.6; P < 0.018) for *S. pectinata* (

Table 4; Annexe 10). Contrary to what was expected, exchangeable P concentration was not higher in limed peat (lime treatment F < 2.6 and P > 0.109 for *C. paleacea* and *S. pectinata*) and was even lower in *C. paleacea* leaves from limed plots (lime treatment F = 8.6; P = 0.036) (

Table 4; Annexe 10). As a result, lime doubled the very low N:P ratio in leaves of *C. paleacea* by almost two times (lime treatment F = 16; P = 0,013) (
Table 4; Annexe 10).

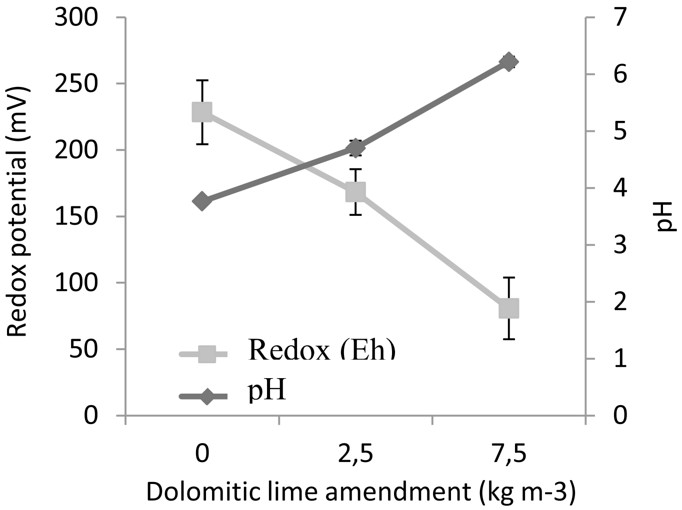

Figure 6 Redox potential in peat root zone evolved in the opposite direction of the pH as a function of lime dose applied (mean ± SE). Soil data from both species are included in the means (n=30).

Table 4 Lime addition effect on peat (soil exchangeable) and leaf nutrient concentrations in *C. paleacea* and *S. pectinata* plots in greenhouse experiment. Only significant differences are listed. Concentrations are given in mg g^{-1} (mean ± SE). (n=9)

Lime	Peat nutrient concentrations					Leaf nutrients	
(kg)	[Ca]	[Mg]	[Fe]	[Mn]	[Al]	[P]	[N:P]
C. paleacea							
0.0	1.2 (0.06)	1.4 (0.1)	0.1 (0.01)	0.02 (0.003)	0.2 (0.003)	1.5 (0.2)	9.4 (2)
2.5	6.7 (0.3)	4.9 (0.2)	0.03 (0.003)	0.03 (0.002)	0.05 (0.009)	1.0 (0.1)	18 (1)
7.5	11.9 (0.8)	8.3 (0.3)	0.001 (0.0003)	0.02 (0.001)	0.02 (0.007)	1.0 (0.08)	20 (3)
S. pectinata							
0.0	1.2 (0.06)	1.6 (0.1)	0.008 (0.01)	0.03 (0.003)	0.2 (0.003)	1.8 (0.3)	9.4 (3)
2.5	6.7 (1.0)	5.0 (0.6)	0.04 (0.01)	0.03 (0.003)	0.6 (0.02)	1.3 (0.1)	16 (1)
7.5	12.1 (0.5)	8.6 (0.3)	0.002 (0.0004)	0.02 (0.003)	0.01 (0.001)	1.2 (0.1)	16 (2)

Discussion

Phosphorus fertilization

General growth improvement with P fertilizer support the hypothesis that P addition would help plants adapting to the harsh conditions of salt contaminated cutover bogs. The positive effect of P can be explained through the leaf N:P ratio, which is an important indicator of N or P limitations for plant growth. According to Meuleman (2010), when the ratio is higher than 16, it indicates P limitation whereas a ratio lower than 14 indicates N limitation. In this field experiment, N:P ratio was 14.5 in presence of P and near 25 without P, demonstrating a P limitation when peat extracted fields were contaminated by sea water. A spill of rock phosphate in a pond nearby the experimental site at Pokesudie led to lush re-colonisation of plants around the pond (Breathnach, 2011, personnal communication). Addition of rock phosphate was also found to promote the establishment of vascular plants in peat extracted bogs not contaminated by salt (Ferland & Rochefort, 1997) or the establishment of *Polytrichum strictum* (Sottocornola, *et al.* 2007) and other bryophytes in degraded blanket bog (O'Toole & Synnott, 1971). In salt marshes restoration, P fertilizer is sometimes applied, but N fertilization is predominant (Zedler 1984; Broome *et al.* 1988). Our results point to the conclusion that P fertilization can be efficiently applied in salt contaminated cutover bogs at the rate of 9 g per transplant or 50 g m^{-2} to improve the establishment of salt marsh transplants. After several attempts to rehabilitate salt contaminated cutover bogs, rock phosphate amendment (applied directly in transplants holes as well as spread over the plots) appears a good step forward.

Lime amendment

The hypothesis that lime amendment would improve vegetation growth by increasing pH and Ca and Mg availability is partially invalidated because, in both experiments, lime did not improved plant growth. We had assumed that the addition of lime would improve soil pH to nearby 5.5 or higher, which, in turn would have improved nutrient availability (especially P). If Al availability can be reduced in soil, P availability for plants will be greater (Griffin, 1971; Ryan & Smillie, 1975; Haynes, 1982; Brady & Weil, 2003). In the present study, P availability in peat did not improved following lime addition. P concentration in leaves was even 1.5 times lower in heavily limed plots. The addition of large amounts of lime to acid waterlogged soils must have encourage the precipitation of Al^{3+} in hydroxyl-Al polymers, which create new adsorption surfaces for phosphates in soil (Haynes, 1982). Similar results were noticed in other experiments for different types of acid soils, where low soil pH was raised by the addition of lime, but decreased P availability (Murrmann, 1969; Amarasiri & Olsen, 1973; Sumner, 1979). As expected, potentially toxic Al (Al^{3+}) was found in lower concentration in limed plots whereas Ca and Mg concentrations were higher. One of the visible and expected effects of high Al concentration in substrate is a stunted root system (Munns, 1965). Yet, plants in the substrate with higher Al concentration (un-limed plots) did not exhibit lower belowground biomass than plants grown in substrate with lower Al concentrations. Similarly lower Ca and Mg availability (un-limed plots) did not influence plant growth. Lime treatment also decreased dramatically the concentrations of micronutrients such as Fe and Mn in peat, which are important for enzymes activation and chlorophyll synthesis in plants (Raven *et al.* 2003). Their lower concentrations in limed plots could be responsible for the poor growth observed in the greenhouse experiment, in concert with the lower P absorption observed in presence of lime.

In the greenhouse experiment, redox potential, which reflects the availability of oxygen in soil, was dramatically reduced by lime addition. It is probably caused by an increased microbial activity allowed by the more neutral pH, that in turn consumed more oxygen (Brady & Weil, 2003). Soil temperature was warmer in all greenhouse plots than in the field, which may also have increased microbial activity. However, redox potentials found in natural salt marshes (Mansfield & Bärlocher, 1993) are lower than what was found in this study (field and greenhouse plots), so it is probably not the most critical abiotic condition to explain poor growth of salt marsh plants introduced in the two experiments. Nevertheless, *Spartina pectinata* shoots were taller with intermediate dose of lime (2.5 kg m^{-3}) therefore in suboxic soil condition. Other studies have reported that coleoptile of *Spartina alterniflora* Loisel. grows faster in anoxia to quickly reach oxygenated soil (Linthurst, 1980; Wijte & Gallagher, 1996a; Wijte & Gallagher, 1996b). The same faster shoot growth was not observed for *Carex paleacea*. Peat was limed 2.5 months prior to the greenhouse experiment to reach a stable pH before plant introduction. Since soil processes are very different in aerobic and anaerobic conditions, it would have been probably more appropriate to let the pH stabilized after incorporating water in experimental tanks rather than before. More stable conditions might be more favorable for plant growth especially under harsh conditions.

In the greenhouse experiment, un-limed plants appeared to be N limited according to their N:P ratio (9.8 in control units *vs* higher than 16 in limed units). N fertilization could thus be an interesting avenue in future experiments, as it is widely used in salt marshes restoration where N is the most limiting nutrients for vegetation growth (Broome *et al.* 1975; Zedler 1984; Kiehl *et al.* 1997; Broome *et al.* 1998; Niedowski 2000; Cargill & Jefferies, 2011). Moreover, intermediate dose of lime could be worth testing since the low doses applied in the field experiments induced suboptimal leaf N:P ratios whereas the high doses applied in the greenhouse experiments led to supra-optimal leaf N:P ratios.

Salt marsh vegetation introduction

The hypothesis that salt marsh vegetation would proliferate and be able to germinate in salt contaminated cutover bogs is confirmed. The higher cover of introduced plants and higher aerial biomass found in *Carex paleacea* plots proved that it can be well adapted to grow in this environment. The slower response of *Spartina pectinata* is probably only due to species intrinsic differences. The use of salt marsh diaspores instead of transplants significantly improved species diversity but plant covers were low, which is probably related to the greater integrity of transplants compared to rototilled salt marsh diaspores. In another study of plant introduction in salt contaminated cutover bog, Montemayor (2006) found that *S. pectinata* exhibits high survival rates compared to *Juncus balticus*.

Breathnach (2008) found that hay transfer (technique consisting in collecting aerial parts of vegetation using a mower than spreading it over the ecosystem to be restored) from salt marsh areas dominated by *S. pectinata* gives better results than hay transfer from areas in the cutover bog dominated by *S. pectinata* or *Juncus bufonius*. Those studies did not include data on *C. paleacea*, which was clearly growing better than *S. pectinata* in the present study. However, plant cover remained low even in the best treatments, leaving room for spontaneous vegetation growth. A limitation to fast plant establishment in the transplantation plots might be the high water level conditions during transplantation of *C. paleacea* and *S. pectinata,* in June 2011. Planters created much more disturbances in the soft substrate than in the firmer substrate that was present during the application of the other treatments (salt marsh diaspores transfer and control treatments).

Germination rates of *S. pectinata* in greenhouse were significantly higher than those of *C. paleacea* (near 0 %). Callawayl & Josselyn (1992) found that *Spartina alterniflora* had higher germination rates in fresh water than in sea water but no information was found about *S. pectinata* or *C. paleacea* germination rates in the literature.

Solidago sempervirens was absent from the salt marsh borrow plots in the bogs but reached 10 % cover in the salt marsh one year after diaspores removal and recovery. The species is known to require a lot of sun to proliferate, so the bare soil left after diaspores removal in natural salt marshes most likely improved its growth. We assume that this species had low cover in the salt marshes borrow plots before transfer, explaining its absence in the bogs where diaspores were transferred. Marsh superficies harvested with rototiller were not greater than 12 square meters, were linear and recovered well. Rototiller probably facilitates the recovery of the borrowed area by removing only the top proportion of the vegetation. More studies should be made to determine the optimal size and shape of the areas that are collected using a rototiller, while allowing fast recovery of the borrowed area.

Implications for management

The present study showed that rock phosphate addition improves the establishment of all plant material introductions by providing P, which is limiting for salt marsh vegetation in bogs. The effects of P leaching on surrounding coastal habitats should however be investigated if large areas are intended to be fertilized, to avoid eutrophication problems (Carpenter *et al.* 1998). Transplantation of *Carex paleacea* is recommended because it led to higher introduced vegetation cover and aerial biomass whereas salt marsh diaspore transfer is recommended to promote species diversity. This last technique is also more suitable for rehabilitation of large superficies. Liming of salt contaminated and waterlogged peat substrate is not recommended to avoid vegetation growth problems through P, trace element and oxygen deficiencies. However, it could be interesting to try another amendment such as Gypsum, to minimize changes in pH while providing Ca which is much lower in bogs than in salt marshes. N fertilizers could also be tested in combination with P fertilization to avoid inducing N limited plant growth.

Chapitre 3 : Conclusion générale

Cette étude est la quatrième au GRET à tenter d'optimiser la ré-végétalisation des bogs exploités contaminés par le sel au Nouveau-Brunswick (Montemayor, 2006; Mouneimne & Price, 2007; Breathnach, 2008; Quinty, 2009). Ceux-ci demeurent essentiellement dénudés, présentant un sol de tourbe à nu, plus d'une décennie après l'envahissement par l'eau de mer. La végétation introduite dans les tourbières contaminées par le sel est exposée à la salinité, le manque d'oxygène causé par une nappe phréatique située près de la surface de la tourbe, par l'acidité et par la faible disponibilité des éléments nutritifs. Afin d'estomper l'effet négatif de la salinité et du manque d'oxygène, les marais salés ont été utilisés comme site d'emprunt pour le matériel végétal. Les défis subsistant sont donc l'acidité ainsi que la faible disponibilité des éléments nutritifs.

Une expérience sur le terrain combinait la transplantation de plantes et le transfert de diaspores de marais salés, de concert avec une fertilisation de roche phosphatée et une application de chaux dolomitique. Une expérience en serre combinait aussi la transplantation de plantes de marais salés en présence de trois doses de chaux dolomitique afin de cibler la dose optimale à appliquer.

Les résultats suggèrent que le phosphore est limitant dans les bogs exploités contaminés par le sel pour la végétation de marais salés. L'ajout de roche phosphatée a donc eu un effet positif marqué sur tous les types de matériaux végétaux testés. La transplantation de plantes de marais salés a aussi entraînée une croissance de la végétation introduite supérieure à celle obtenue avec le transfert de diaspores. C'est *Carex paleacea* qui a obtenu les biomasses et couverts de végétation introduite les plus élevés. Le transfert de diaspores de marais salés s'implante plus lentement que les plantes transplantées, mais la diversité d'espèces produite est beaucoup plus élevée. L'utilisation de chaux dolomitique quant à elle n'est pas recommandée pour l'instant.

L'effet positif du phosphore sur la végétation de marais salé en bogs exploités contaminés par le sel est une avancée. La végétation de marais salés est aussi une avenue prometteuse pour la re-végétalisation de ces bogs. La transplantation est efficace mais manuellement laborieuse tandis que le transfert de diaspores de marais salés favorise une biodiversité plus riche, mais est plus lent à s'implanter. En revanche, cette méthode pourrait être plus facilement mécanisable pour la re-végétalisation de grandes surfaces de tourbières.

Lors d'expériences futures, on pourrait tester d'autres amendements riches en calcium, mais qui n'augmenteraient pas de façon draconienne le pH du substrat, tel que le gypse. De plus amples investigations seraient aussi nécessaires pour s'assurer que les zones d'emprunt dans les marais salés peuvent se régénérer tout aussi bien lorsque les superficies récoltées sont supérieures à celles utilisées dans cette expérience (12 m^2). L'effet de l'utilisation de roche phosphatée devrait aussi être investigué afin de vérifier qu'il n'y ait pas de risques d'eutrophisation des habitats côtiers en raison du lessivage d'éléments nutritifs, lors de la re-végétalisation à grande échelle de bogs exploités contaminés par le sel. Les résultats d'analyses foliaires montraient aussi une limitation en azote pour les plantes, ce qui pourrait être approfondie lors d'expériences futures impliquant des fertilisants azotés.

Les bogs exploités contaminés par le sel sont des milieux humides ayant un bon potentiel de ré-végétalisation grâce à l'utilisation de végétation de marais salés et de fertilisants. Les efforts doivent être maintenus afin de cerner la méthode optimale pour re-végétaliser à grande échelle ces écosystèmes.

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Annexes

Annexe 1 Bare peat in Pokesudie salt contaminated cutover bog, 11 years after salt contamination (June 2011).

Annexe 2 *S. pectinata* plugs collected in Shippagan salt marsh (left) were transplanted in plots of Shippagan bog (right) in combination with amendment treatments.

Annexe 3 Marsh diaspore collection in Pokesudie salt marsh. Diaspore collection was done after a rototiller has been passed over the area selected in the salt marsh (left). Right picture is a zoom on the collected material that includes aerial parts of vegetation and 5 cm of salt marsh substrate.

Annexe 4 Representation of one of the five blocks of the greenhouse experiment (left), comprising six experimental units. One unit corresponds to a container and includes six transplants as well as two groups of 50 seeds, all of the same species (right).

Annexe 5 ANOVA for soil amendments and introduced plant materiel effects on vegetation covers in field. Significant P values are in boldface (n=80).

		Introduced[1] veg cover		Spontaneous[2] veg cover		Total cover	
Sources	d.f	F	P	F	P	F	P
Blocks	3						
Veg	4	46	<0.001	7.7	0.004	1.6	0.200
Lime	1	0.0	0.973	0.02	0.883	0.2	0.676
P	1	16	**0.004**	10.8	**0.003**	21	**<0.001**
Veg × Lime	4	1.7	0.193	0.4	0.822	0.2	0.938
Veg × P	4	3.7	**0.019**	1.4	0.277	0.7	0.620
Lime × P	1	0.2	0.641	0.6	0.465	0.5	0.471
Veg × Lime × P	4	1.0	0.437	0.8	0.552	0.4	0.783
Error	57						
Total	79						

[1] Vegetation from the salt marshes that have been implanted in the salt contaminated cutover bogs is called «introduced vegetation».

[2] Vegetation that spontaneously grows in the salt contaminated cutover bogs is called «spontaneous vegetation». It is mainly *Juncus bufonius* and *Eriophorum angustifolium*.

Annexe 6 ANOVA for soil amendments and introduced plant material effects on biomass in field. Significant P values are in boldface (n=80).

		Spontaneous[1] veg aerial biomass		Introduced[2] veg aerial biomass		Total aerial biomass		Underground biomass		total biomass	
Sources	d.f	F	P	F	P	F	P	F	P	F	P
Blocks	3										
Veg	4	3.5	**0.026**	30.9	**<0.001**	0.8	0.596	1.1	0.381	2.2	0.099
Lime	1	0.3	0.610	4.3	**0.043**	0.02	0.892	0.3	0.565	0.2	0.645
P	1	4.8	**0.040**	7.5	**0.008**	8.74	**0.010**	1.9	0.177	8.3	**0.006**
Veg × Lime	4	0.2	0.952	4.2	0.048	0.3	0.889	1.9	0.146	0.1	0.996
Veg × P	4	1.6	0.208	1.3	0.281	0.9	0.562	1.0	0.446	0.3	0.866
Lime × P	1	1.3	0.264	1.9	0.171	0.5	0.506	1.6	0.962	0.8	0.367
Veg × Lime × P	4	0.7	0.608	1.6	0.179	0.4	0.796	0.2	0.962	0.9	0.485
Error	57										
Total	79										

[1] Vegetation from the salt marshes that have been implanted in the salt contaminated cutover bogs is called «introduced vegetation».

[2] Vegetation that spontaneously grows in the salt contaminated cutover bogs is called «spontaneous vegetation». It is mainly *Juncus bufonius* and *Eriophorum angustifolium*.

Annexe 7 ANOVA for amendments and introduced plant material effects on leaf nutrients status in field. Foliar nutrients were analysed in C. paleacea and S. pectinata leaves. Significant P values are in boldface (n=40).

		Foliar nutrients							
		Phosphorus (P)		Calcium (Ca)		N:P Ratio		Ca:Mg Ratio	
Sources	d.f	F	P	F	P	F	P	F	P
Blocks	3								
Veg	1	13	**0.002**	1.1	0.317	1.3	0.270	2.2	0.156
Lime	1	1.9	0.188	6.4	**0.022**	0.8	0.398	9.1	**0.007**
P	1	19	**0.001**	0	0.953	20	**0.004**	0.5	0.511
Veg × Lime	1	0.1	0.779	0.5	0.513	0	0.841	1.2	0.285
Veg × P	1	3.1	0.096	0	0.858	0.1	0.744	3.3	0.083
Lime × P	1	0.8	0.372	0.2	0.650	0.7	0.411	0.8	0.391
Veg × Lime × P	1	0.8	0.399	1.1	0.320	0	0.951	0.8	0.377
Error	21								
Total	31								

Annexe 8 ANOVA for amendments effects on pH and peat nutrients status in field. Peat substrate was sampled in *S. pectinata* and July marsh layer treatment plots. Significant P values are in boldface (n=40).

	Peat nutrients and pH					
		pH			Calcium (Ca)	
Sources	d.f	F	P	d.f	F	P
Blocks	3			3		
Rep	4			1		
Lime	1	8.9	**0.004**	1	6.5	**0.025**
P	1	2.6	0.116	1	0.1	0.808
Lime × P	1	0.0	0.844	1	0.4	0.527
Error	57			24		
Total	79			31		

Annexe 9 ANOVA for peat chemical characteristics, *C. paleacea and S. pectinata* germination, seedling shoot height, mature plant height, number of leaves, aerial, belowground and total biomass. *C. paleacea* and *S. pectinata* were not compared because their morphology is different (n=15).

		Chemical characteristics				**Germination**				**Mature plants**							
		pH		Redox		Germination rates		Height of shoots		Height of plants		Aerial biomass		Belowground biomass		Total biomass	
Sources	d.f	F	P	F	P	F	P	F	P	F	P	F	P	F	P	F	P
C. paleacea																	
Blocks	4																
Lime	2	442	**<0.001**	13	**0.003**	0.46	0.640	1.1	0.394	6.0	**0.025**	11	**0.017**	0.1	0.912	1.4	0.281
Error	8																
Total	14																
S. pectinata																	
Blocks	4																
Lime	2	296	**<0.001**	14	**0.001**	0.14	0.872	8.2	**0.006**	0.1	0.953	4.5	**0.035**	3.8	0.075	28	**0.003**
Error	8																
Total	14																

Annexe 10 ANOVA testing the dolomitic lime effect on peat exchangeable nutrients and foliar nutrients. Foliar and peat nutrients were analysed separately for *C. paleacea* and *S. pectinata* plots (n=9); three out of the five blocks were analysed). Only nutrients for which statistically significant differences were observed are presented. Significant P values are in boldfaces.

		Peat nutrients										**Leaves nutrients**			
		Calcium (Ca)		Magnesium (Mg)		Iron (Fe)		Manganese (Mn)		Aluminium (Al)		Phosphorus (P)		N:P ratio	
Sources	d.f	F	P	F	P	F	P	F	P	F	P	F	P	F	P
C. paleacea															
Blocks	2														
D lime	2	151	**0.002**	437	**<0.001**	67	**0.001**	9.7	**0.029**	359	**<0.001**	8.6	**0.036**	16	**0.013**
Error	4														
Total	8														
S. pectinata															
Blocks	2														
D lime	2	69	**<0.001**	88	**0.005**	8.6	**0.018**	3.5	0.099	23	**0.002**	2.3	0.182	3.0	0.123
Error	4														
Total	8														