Université de Montréal

Épuration d'un effluent piscicole par l'irrigation intensive d'une plantation d'arbres à croissance rapide

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Mémoire présenté à la Faculté des études supérieures
en vue de l'obtention du grade de
Maître ès sciences (M. Sc.)

Janvier 2007

Université de Montréal
Faculté des études supérieures

Ce mémoire intitulé :

Épuration d'un effluent piscicole par l'irrigation intensive d'une plantation d'arbres à croissance rapide

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RÉSUMÉ

Plusieurs études récentes ont validé les performances d'arbres, notamment de saules et de peupliers en culture intensive sur courtes rotations (CICR) pour le traitement d'effluents chargés en éléments organiques ou le recyclage de boues usées. L'objectif de ce projet était de démontrer l'efficacité d'espèces de saule et de peuplier pour le traitement d'effluents peu concentrés en mode d'irrigation intensive, en vérifiant leur réponse aux conditions physico-chimiques engendrées par ce traitement et en mesurant leur capacité à retenir le phosphore. L'expérience comportait également un second volet, où un inoculum commercial (MYCORISE®, Premier Tech) de mycorhize arbusculaire, *Glomus intraradices*, était appliqué afin de vérifier si de cette manière, l'absorption du P pouvait être accrue. Les performances de deux espèces de saules et un hybride de peuplier en présence et absence de mycorhizes ont ainsi été testés devant deux concentrations de phosphore. Selon les résultats de cette étude en deux volets, les saules répondent mieux que les peupliers aux conditions d'inondation et semblent bénéficier davantage de la présence des mycorhizes, bien que la colonisation par l'inoculum utilisé ait réussi chez les deux espèces. En effet, il a été observé que sous une irrigation intensive d'environ 140 mm d'eau par jour, *Salix viminalis* maintenait un niveau adéquat d'azote foliaire (concentration foliaire de 20 mg N/g) et atteignait, après deux ans de croissance, des rendements comparables à ceux obtenus avec une irrigation régulière dans des conditions de sol similaire (1 TMA/ha). À l'opposé, *Populus* NM5 a démontré en conditions d'inondation une faible productivité et des signes de déficience nutritionnelle (concentration foliaire de 10 mg N/g) très tôt en saison. Par ailleurs, nous avons observé qu'une colonisation mycorhizienne des racines permettait à *Salix viminalis* et *Salix miyabeana* d'augmenter de 33% le phosphore total contenu dans leur bois, grâce à une augmentation significative de leur biomasse ligneuse.

Mots clés : phytoremédiation, mycorhizes, phosphore, CICR, saule, peuplier, ligniculture, décontamination.

ABSTRACT

Several recent studies validated the performances of trees, in particular willows and poplars in short rotations intensive culture (SRIC), for wastewater treatment and recycling sludge. The purpose of this project was to show the effectiveness of willow and poplar species for the filtration of an effluent of low concentrations, under intensive irrigation. During this study, we evaluated trees response to the physicochemical conditions generated by the intensive irrigation and their capacity to retain phosphorus. The experiment also included a second part, where a commercial inoculum (MYCORISE®, First Tech) of arbuscular mycorrhiza, *Glomus intraradices*, was applied in order to verify the impact on P absorption. The performance of two species of willow and one poplar hybrid with or without mycorhizes were then tested with two phosphorus concentrations. According to our results, willows present a better response than poplars under flooded conditions and higher benefits associated to the presence of mycorrhizas, although colonization by the inoculums succeeded with both species. Indeed, we observed that under an intensive irrigation of approximately 140 mm of water per day, *Salix viminalis* maintained an adequate foliar nitrogen level (foliar concentration of 20 mg N/g) and reached, after two years of growth, yields obtained under regular irrigation in similar ground conditions (1 tDM/ha). In contrast, *Populus* NM5 showed a low productivity and signs of nutritional deficiency (foliar concentration of 10 mg N/g) very early in season. In addition, we observed that a mycorrhizal colonization allowed *Salix viminalis* and *Salix miyabeana* to increase by 33% their stem's total phosphorus content, because of a significant increase of their wood biomass.

Mots clés : phytoremediation, mycorrhizes, phosphorus, SRIC, willow, poplar, ligniculture, decontamination.

TABLE DES MATIÈRES

LISTE DES TABLEAUX

LISTE DES FIGURES

LISTE DES ANNEXES

LISTE DES ABRÉVIATIONS

°C : Degrés Celsius

AMF : Arbuscular mycorrhizal fungi (mycorhize à arbuscules)

Ca : Calcium

CICR : Culture intensive sur courte rotation

cm : Centimètre

EcMF : Ectomycorrhizal fungi (ectomycorhize)

g : Gramme

ha : Hectare

K : Potassium

K_2O : Oxyde de potassium

Kg : Kilogramme

KOH : Hydroxyde de potassium

L : Litre

m : Mètre

Mg : Magnésium

mm : Millimètre

N : Azote

NH_4 : Ammonium

NO_3 : Nitrate

P : Phosphore

P. NM5 : *Populus nigra* x *P. maximowiczii*

P_2O_5 : Phosphore anhydride

SLA : Specific leaf area

SRIC : Short rotation intensive culture

tDM : ton of dry mass (tonne de matière sèche)

TMA : tonne de matière anhydre

REMERCIEMENTS

Cette recherche a été réalisée grâce au soutien financier de la Société de recherche et de développement en aquaculture continentale (SORDAC) et les Fonds de recherche sur la nature et les technologies (FQRNT). L'inoculum mycorhizien utilisé dans cette expérience a été gracieusement fourni par l'entreprise Premier Tech de Rivière-du-Loup.

Merci tout d'abord à Michel Labrecque, mon directeur, qui m'a accepté dans son équipe avec beaucoup de générosité. J'ai pu enrichir mes connaissances d'une façon incroyable grâce à tes conseils et ta façon de communiquer ta curiosité. Tu m'as permis de développer un regard plus intégral sur notre discipline et ta générosité m'a permis d'acquérir des expériences sans pareil qui ont dépassé largement tout ce en quoi je m'attendais en m'engageant dans la maîtrise.

Merci à Jacques Brisson, mon co-directeur. Je te considère comme un scientifique passionné et un conteur captivant. J'admire ta rigueur qui a souvent remis en question ce que je proposais, dans le but de toujours améliorer la portée de mes recherches. Plus que tout, ta propension à transmettre ton émerveillement devant la nature et les lois qui la structurent m'ont aidé à comprendre comment moi aussi j'y suis attachée et à quel point je suis prête à m'y dévouer.

Je tiens à remercier Trian Ion Teodorescu, pour son savoir immense et son expérience incomparable. Tu as été celui qui m'a montré l'essentiel : tu m'a appris à instituer des relations entre les idées hautes et leurs incarnations concrètes, sur le terrain.

Merci à Marc Saint-Arnaud et Laetitia Lioussanne pour m'avoir aiguillée dans cette aventure mycorrhizienne. Votre aide fut plus qu'appréciée. Gabriel Teodorescu et tous les étudiants du laboratoire Brisson : Vincent, Florent, Marie-Ève, Joëlle, Étienne, Bastien, Marie et Carole. Je vous suis très reconnaissante! Merci pour votre présence. Merci à Jérémy Locklear et à Roger pour le dur labeur que vous m'avez offert, à la sueur

de vos fronts. Un énorme merci à Stéphane Daigle, Marie-Claude Turmel et Hélène Lalande pour leur support technique très apprécié.

Merci à toute l'équipe de l'Institut de recherche de Geraardsbergen en Belgique, notamment Bart Vandecasteele, Pierre Van Peteghem, Linda Meiresonne, Boudewijn Michiels et Bruno De Vos. Mon aventure dans votre contrée flamande fut hautement enrichissante d'un point de vue scientifique autant qu'humain.

Enfin, j'aimerais remercier ma famille et mes amis pour leur grande compréhension et leur infatigables encouragements depuis le début de cette expérience. Nicolas, à qui je réserve une admiration sans bornes, merci mille fois. Ta présence me donne la force et la confiance dont j'ai besoin. Encore merci.

DÉCLARATION CONCERNANT LES ARTICLES SCIENTIFIQUES

Liste des articles scientifiques

I) Maud Fillion, Jacques Brisson, Trian Ion Teodorescu, Sébastien Sauvé et Michel Labrecque
Performance of a willow and a poplar species in short rotation intensive culture for phosphorus uptake under intense irrigation
Article en préparation, destiné à la revue *Biomass and Bioenergy*

II) Maud Fillion, Michel Labrecque, Jacques Brisson
Phosphorus retention efficiency of one hybrid poplar and two willow species using arbuscular mycorrhizal fungi
Article en préparation, destiné à la revue *Journal of Environmental Quality*

Maud Fillion a été la principale auteure des deux articles scientifiques présentés ci-après. Ses directeurs Michel Labrecque et Jacques Brisson ont établi la problématique, supervisé les actions sur le terrain qu'elle a elle-même opérées avec l'aide de Trian Ion Teodorescu et révisé les textes. Sébastien Sauvé a lui aussi collaboré en tant que réviseur du premier article.

- **Chapitre 1. INTRODUCTION**

En vertu d'une entente conclue entre le ministère du Développement durable, de l'Environnement et des Parcs et les pisciculteurs québécois, les effluents en phosphore d'une pisciculture ne doivent pas excéder 4,2 Kg par tonne de poisson produit (Ouellet, 1999). Pour respecter cette limite, plusieurs solutions ont été envisagées, par l'entremise du choix des moulées et de l'entretien des étangs par exemple, et plus récemment, par l'utilisation de marais filtrants (Summerfelt et al., 1999; Naylor et al., 2003). Bien qu'elles s'inscrivent inévitablement dans le processus de réduction des émissions de phosphore, ces avenues ne touchent que partiellement le problème. Le traitement de ces effluents étant plus problématique de par le fait qu'ils se caractérisent par un fort débit et une concentration en phosphore inférieure à 0,5 mg/L (Morin, 1998). Devant de telles conditions, l'exploitation du potentiel des végétaux pour absorber les contaminants organiques constitue une technologie adaptée. En raison de leur haut taux de transpiration, les végétaux cultivés peuvent réduire les quantités d'eau rejetées dans l'environnement tout en bénéficiant des nutriments transportés par l'eau usée pour leur croissance et leur développement (Hall et al., 1998). L'utilisation d'une culture ligneuse pour ce type de filtration pourrait également entraîner un revenu supplémentaire pour le pisciculteur par la vente du bois produit. Le potentiel de réduction des émissions en phosphore d'un effluent piscicole, par l'irrigation intensive d'une plantation d'arbres à croissance rapide, soulève ainsi un intérêt écologique et économique.

Ce premier chapitre est consacré à la mise à jour des connaissances sur les processus de traitement des eaux par les arbres ainsi que la technique de culture intensive sur courtes rotations (CICR) sur laquelle est basée la présente étude. Les facteurs influant sur le potentiel filtrant des arbres, tout comme les conséquences d'une irrigation intensive et les perspectives qu'offre la mycorhization, seront aussi des champs abordés ci-après afin de mieux cerner toutes les implications du traitement d'un très large volume d'eau combiné avec de faibles concentrations de polluants.

Valorisation des eaux usées

Les contaminants organiques contenus dans les effluents comportent généralement des éléments nutritifs tels que l'azote et le phosphore, susceptibles de stimuler la croissance de végétaux dans les écosystèmes aquatiques. Leur déversement dans les cours d'eau naturels engendre souvent un enrichissement excessif qui peut affecter les communautés végétales et animales et modifier sérieusement l'intégrité écologique du milieu aquatique récepteur; un phénomène que l'on nomme eutrophisation. Cette forme de pollution due à l'activité humaine peut aussi, dans certains cas, entraîner le développement de cyanobactéries, ou algues bleues. Ces efflorescences algales ne sont pas sans conséquence, puisque certaines espèces libèrent des toxines dangereuses pour l'homme et les animaux. Au Québec, la prolifération d'algues bleues dans les plans d'eau est un phénomène observé sur une portion grandissante du territoire. Pour éviter les déversements polluants en milieux naturels, les eaux usées industrielles ou urbaines, les boues d'épurations ou encore les déchets agricoles, sont parfois utilisés comme fertilisants agricoles et sylvicoles, ce qui permet des rendements accrus pour les végétaux en culture à de faibles coûts (Perttu et Kowalik, 1997). On décrit ce procédé par lequel des végétaux sont utilisés pour valoriser des résidus organiques polluants pour nos écosystèmes par le terme phytoremédiation (Licht et Isebrands, 2005). En plus de l'absorption directe et de la métabolisation des éléments organiques par les plantes, la couverture végétale peut également bénéficier d'une activité microbienne et fongique au niveau de la rhizosphère, ce qui optimise le recyclage des nutriments (Aronsson et Perttu, 2001).

Depuis des années, les peupliers (*Populus spp.*) et les saules (*Salix spp.*) sont plantés en bandes riveraines dans les milieux agricoles afin de retenir les fertilisants dans l'eau de ruissellement et de limiter ainsi le déversement des polluants dissous vers les cours d'eau naturels (Lowrance et al., 1984). Encore aujourd'hui, ces végétaux sont parmi les plantes ligneuses les plus couramment utilisées en phytoremédiation (Licht et Isebrands, 2005). L'efficacité de ces arbres vient principalement du fait qu'ils possèdent un réseau racinaire très fourni, un taux de croissance élevé et une flexibilité à croître dans divers milieux (Labrecque et al., 1997; Weih, 2004). Leur importante production de biomasse est en

général associée à un recyclage rapide des éléments et une consommation élevée en eau (Mirck, 2002), ce qui augmente de façon considérable le rendement de filtration par unité de surface de plantation par rapport à d'autres espèces.

Culture intensive sur courtes rotations

On appelle culture intensive sur courtes rotations (CICR) la technique selon laquelle une plantation à haute densité de plantes ligneuses à croissance rapide est exploitée afin de maximiser les rendements à l'hectare. Cette technique fait également appel à des plantes qui ont la capacité de rejeter vigoureusement après la taille ou le recepage des portions aériennes. Ainsi, la biomasse produite par ce type de culture peut être récoltée à intervalles courts de 2 à 4 ans selon les conditions et les espèces utilisées. On estime que de tels systèmes de culture ont une durée de vie économique de 25 à 30 ans (Makeschin, 1999). Aujourd'hui, la production de biomasse ligneuse à visées commerciales se fait dans plusieurs pays pour répondre à divers marchés (Licht et Isebrands, 2005). Plusieurs auteurs ont déjà démontré les facultés épuratrices de ce type de plantation pour la décontamination des effluents chargés en éléments organiques (Lowrance et al., 1984; Perttu et Kowalik, 1997; Elowson, 1999; Aronsson et Bergstrom, 2001; Jonsson et al, 2004, 2006). En revanche, bien que plusieurs chercheurs aient travaillé sur le potentiel épurateur des salicacées, peu de littérature concerne les effluents à faible charge.

Pouvoir filtrant

L'efficacité épuratrice d'une plantation d'arbres à croissance rapide peut dépendre de plusieurs facteurs: le type de sol, la concentration des polluants dans l'effluent ou encore l'intensité de l'irrigation, les espèces utilisées, etc. (Jonsson et al., 2004). En effet, la rétention des éléments sur les particules de sol (l'adsorption) est plus importante dans les sols argileux, alors que la captation par les arbres des nutriments transportés par l'effluent (l'absorption) est supérieure dans les conditions où le sol est pauvre. Par exemple, dans un

système à gravier, basé sur la culture hydroponique, il a été observé que le saule retenait 91% du phosphore contenu dans l'eau d'irrigation (Mant et al., 2003). Dans un système avec sol, l'efficacité de l'arbre pour le phosphore se situe entre 40% et 80%, selon les conditions de l'expérience avec des concentrations en phosphore variant de 0,2 mg/L à 15 mg/L (Perttu et Kowalik, 1997; Mirck et al., 2005). Dépendamment des caractéristiques physico-chimiques du milieu et de l'effluent en présence, l'atteinte de l'objectif de filtration visé repose sur l'ajustement judicieux de chacun des facteurs en fonction des autres. Par exemple, la concentration des polluants dans l'eau d'irrigation fera varier le taux d'irrigation applicable pour optimiser l'efficacité épuratrice de la plantation. En effet, des études ont démontré qu'une plantation irriguée avec 10 ou 15 mm d'eau par jour avec des concentrations de phosphore variant de 4 à 15 mg/L offrait un rendement comparable à une plantation irriguée avec plus de 50 mm par jour avec des concentrations inférieures à 0,5 mg P/L (Perttu et Kowalik, 1997; Elowson, 1999; Jonsson, 2006). Le pouvoir filtrant d'une plantation est aussi fortement lié au potentiel d'évapotranspiration de la surface irriguée (Elowson, 1999). Par le phénomène de transpiration, la végétation participe à la réduction de l'écoulement et à l'allongement du temps de résidence du flux, ce qui augmente la concentration en nutriments dans le sol et facilite l'absorption par les racines (Hall et al., 1998; Pauliukonis et Schneider, 2001). Les orthophosphates représentent la forme du phosphore la plus disponible pour une utilisation par les végétaux, mais aussi celle qui est la plus réactive chimiquement. Les orthophosphates regroupent les formes oxydées du phosphore ($H_3PO_4^-$, HPO_4^{2-}, PO_4^{3-}) et leur répartiion dépend du pH du milieu. En somme, un des principes fondamentaux de la phytoremédiation est d'associer l'espèce appropriée au site de contamination. De même, les paramètres liés à l'irrigation doivent être réglés pour répondre aux conditions de sol, de climat ainsi qu'à la nature et la concentration du contaminant à extraire.

Irrigation intensive

Dans les systèmes de culture de plantes quel qu'il soit, les quantités de fertilisants à appliquer sont habituellement déterminées selon l'apport en azote. Cet élément limitant

pour la croissance des plantes devient très mobile dans un sol irrigué et, tout comme le phosphore, les pertes par lessivage constituent une source importante de pollution pour les nappes d'eau adjacentes. Certaines études démontrent que 100 Kg/ha d'azote disponible semble être une dose adéquate pour l'établissement des saules et des peupliers en culture intensive sur courte rotation tout en minimisant les risques de lessivage des nitrates (Labrecque et al., 1998; Elowson, 1999; Berthelot et al., 2000). Toutefois, dans le cas où l'effluent serait très dilué, la limitation n'est plus imposée par la quantité de nutriments apportés, mais plutôt par la capacité du sol à retenir l'eau et surtout, la tolérance des arbres aux conditions édaphiques qu'engendre l'irrigation intensive. La plus importante contrainte pour la croissance des arbres en conditions d'inondation est le manque d'oxygène. En effet, l'irrigation intense d'un sol peut limiter les échanges gazeux avec l'atmosphère au point de causer un déficit important en oxygène au niveau des racines (Good et al., 1992; Kozlowski, 1997). Ce phénomène est d'autant plus important dans un sol lourd (argileux) où l'espace entre les particules de sol est réduit par rapport à ce qu'on retrouve dans les sols sablonneux. La plupart des espèces de saule et de peuplier sont naturellement adaptés aux conditions anaérobiques des zones riveraines et montrent une bonne tolérance à l'excès d'eau (Hallgren, 1989; Licht et Isebrand, 2005). En général, cette tolérance est directement liée à l'aptitude des arbres à développer des adaptations physiologiques associées au transport de l'oxygène vers les racines. L'hypertrophie de la tige et l'accroissement du nombre de lenticelles, l'oxydation de la rhizosphère et l'augmentation de la porosité racinaire sont entre autres des exemples d'adaptation aux conditions physico-chimiques engendrées par l'inondation d'un sol (Hallgren, 1989). Encore ici, le choix de l'espèce est très important puisqu'une variation intraspécifique de la tolérance à la surirrigation est observable chez les *Salicaceae* (Hallgren, 1989; Liu and Dickmann, 1992).

Mycorhizes

Dans un système de filtre végétal, le processus de rétention des polluants n'est pas uniquement généré par la plante elle-même, mais aussi par les microorganismes de la rhizosphère (Mirck et al., 2005). Par exemple, en échange de carbone, les champignons

mycorhiziens associés aux racines assurent une plus grande translocation de certains éléments limitant vers la plante hôte (Backhaus et al., 1986). Leur présence peut ainsi augmenter de façon significative la capacité de rétention de certains éléments par la plante. Les deux types d'associations mycorhiziennes les plus répandus sont les mycorhizes à arbuscules (AMF), le champignon ayant son siège à l'intérieur des cellules de la racine, et les ectomycorhizes (EcMF), le champignon étant situé à l'extérieur des cellules de la racine (Jones et al., 1998; van der Heijden, 2001). Si leurs effets sur les plantes sont relativement les mêmes, certains auteurs s'entendent pour dire que les AMF prédominent dans les endroits principalement limités en phosphore alors que les EcMF prévalent dans les milieux déficients en azote (Read, 1989; van der Heijden, 2001). D'ailleurs, de nombreuses expériences dénotent que les AMF sont majoritaires chez les jeunes plants en croissance offrant ainsi des bénéfices à court terme contrairement aux avantages à long terme que semblent procurer les EcMF (Dhillion, 1994; Van der Heijden, 2001; Khasa et al., 2002). Quoiqu'il en soit, les peupliers et les saules font partie des rares espèces qui forment des associations avec les deux types de mycorhizes (Lodge, 1989; Khan, 1993; Dhillion, 1994). Leur présence peut avoir un impact majeur sur la croissance et la nutrition des plantes, en plus d'augmenter la protection des racines contre divers pathogènes (Khasa et al., 2002; Helgason et al., 2006). Bref, pour tous les avantages que les mycorhizes procurent aux plantes, la perspective de les utiliser pour la filtration du phosphore dans les effluents dilués des pisciculteures semble intéressante. Pourtant, relativement peu d'expériences ont été menées au sujet de l'impact des mycorhizes dans des stratégies de phytoremediation de polluants organiques et peu d'investigations ont été faites sur la colonisation des espèces de *Populus* et de *Salix* par des inoculums commerciaux développés pour le marché agricole.

Objectifs

L'étude présentée ici visait à analyser le potentiel d'une plantation d'arbres à croissance rapide pour la rétention du phosphore provenant d'un effluent dilué. L'expérience a été menée selon deux volets : un premier en milieu naturel, dans une

pisciculture située au sud-est de Montréal, et un second, en conditions semi-contrôlées, conduite au Jardin botanique de Montréal.

En milieu naturel, les objectifs étaient :

1) Vérifier l'hypothèse selon laquelle la croissance des arbres vient réduire le déversement de phosphore provenant de l'effluent piscicole dans les plans d'eau environnants.
2) Analyser la croissance ainsi que le statut nutritionnel d'une espèce de saule et de peuplier hybride dans les conditions physico-chimiques engendrées par l'irrigation continue d'un sol lourd.

Suivant la mise en place d'un dispositif de plantation à forte densité, une analyse a pu être menée sur la capacité de deux espèces (saule et peuplier) à extraire le phosphore d'un effluent avant qu'il ne soit déversé dans les cours d'eaux naturels. L'étude a permis de voir l'impact d'une charge de contaminants et d'une irrigation importante sur de jeunes arbres en plus d'évaluer la performance de ce type d'intervention en conditions réelles.

En milieu contrôlé, l'objectif était :

1) Déterminer l'impact d'un inoculum commercial de AMF (*Glomus intraradices*) sur la rétention du phosphore par trois espèces (deux saules et un peuplier) soumises à deux concentrations de phosphore différentes.
2) Comparer la performance de rétention du phosphore des trois espèces choisies.

En utilisant un dispositif de plantation en pot, une étude a pu être menée sur les impacts d'une inoculation d'un champignon mycorhizien à arbuscule sur la performance de rétention du phosphore de trois espèces utilisées commercialement en CICR au Québec. Cette approche visait à explorer le potentiel d'une association mycorrhizienne pour l'amélioration des capacités épuratrices des arbres utilisés en CICR.

Approches générales

En premier lieu, une plantation de 800 m^2 a été établie au printemps 2004 à la pisciculture de Pierre Vézina à Chartierville dans les Cantons-de-l'est. Le dispositif expérimental a été défini en respect des exigences statistiques mais également en tenant compte de contraintes imposées par l'espace disponible sur le terrain et les divers traitements à appliquer. Deux espèces végétales ont été plantées, soit le saule osier (*Salix viminalis 5027*) et un peuplier hybride soit le peuplier NM5 (*Populus nigra x P. maximowiczii)*. Après une première année de croissance, un système d'arrosage par gicleurs alimentés par une pompe a été installé pour irriguer et ainsi permettre l'épuration des eaux contaminées sur une moitié de la plantation pendant la période de croissance de l'été 2005, l'autre moitié servant de témoin. Des mesures de croissance et de concentration en phosphore dans les différentes parties de la plante ont été réalisées, de même que des mesures sur la concentration en phosphore dans le sol et dans l'eau de percolation. Des lysimètres ont été disposés dans chacun des blocs expérimentaux afin de recueillir ces eaux de percolation. En second lieu, une expérience en milieu semi contrôlé a été conduite sur le site du Jardin botanique. Le dispositif comportait deux espèces de saule (*Salix viminalis* 5027, *S. miyabeana SX64*) et le peuplier hybride NM5 (*Populus nigra x P. maximowiczii*). La moitié des plants du dispositif a été inoculée avec le même inoculum mycorhizien décrit plus haut (*G. intraradices*). Afin de mettre en relief les effets de la mycorhization dans des conditions limitées en phosphore, deux concentrations différentes ont été utilisées, l'une se rapprochant de la teneur d'un effluent piscicole, soit 0,5 mg/L et l'autre suffisamment importante pour modifier le statut nutritionnel des plantes (10 mg/L), sans toutefois fournir un apport trop élevé qui aurait pu affecter la colonisation mycorhizienne (> 15 mg/L P_2O_5).

Organisation du mémoire

Les résultats concluants de ces deux expériences menées en parallèle sont présentés sous forme de deux articles scientifiques distincts constituant les deux prochains chapitres de ce document. Le dernier chapitre de ce travail présente une conclusion générale

permettant de revenir sur les objectifs définis ci-dessus. Enfin, deux annexes présentent à la toute fin de ce document les résultats des ANOVA qui ont été effectués sur les données récoltées en milieu naturel et contrôlé.

- **Chapitre 2.**

PERFORMANCE OF A WILLOW AND A POPLAR SPECIES IN SHORT ROTATION INTENSIVE CULTURE FOR PHOSPHORUS UPTAKE UNDER INTENSE IRRIGATION

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Abstract — In this study, we evaluated a simple and cost-effective way of treating the effluent of a fish farm in southern Quebec, with its large volume (2300 L/min) and low pollutant concentration (0.3 mgP/L), by the intense irrigation of fast-growing deciduous trees. On a plantation established in 2004 from stem cuttings at a density of 20,000 trees per hectare, we investigated growth and nutritional plant response to a high hydraulic regime in two species (*Salix viminalis* and *Populus nigra x P. maximowiczii*), using a comparative approach with measurements from irrigated and control plots. The plantation was irrigated from June to September 2005 with about 140 mm per day. The equivalent of 120 Kg NO_3-N, 40 Kg P_2O_5-P and 85 Kg K_2O-K per hectare per year was applied by means of irrigation with wastewater. No mortality occurred and stem biomass production of both poplar and willow species were not statistically different on irrigated and control areas. However, *Salix viminalis* seemed more tolerant to flooded conditions since these corresponded more closely to its nutritional requirements (foliar concentration of 20 mgN/g). The capacity of *Salix viminalis* to withstand waterlogged conditions could play an important role in the sustainability of a plantation for the filtration of effluent at low pollutant concentration.

INTRODUCTION

Fast-growing trees for biomass production is proposed as an economical and ecological solution to increasing demand for energy, and also for the anticipated shortage of raw

materials for wood-based industries (Licht and Isebrands, 2005). In Quebec for example, pulp and paper and wood panelling manufacturers have recently shown an interest in fiber from willow plantations under short rotation intensive culture (SRIC) (Labrecque and Teodorescu, 2005: Sean and Labrecque, 2006). Production of woody biomass through SRIC leads to several environmental benefits due to the renewable nature of this very productive system and its capacity to recycle organic residue such as sludge, manure or wastewater (Spitzer and Ahamer, 1992).

The efficiency of vegetation as filters has been demonstrated in several field studies conducted in many different countries (Perttu and Kowalik, 1997; Nixon et al., 2001; Mirck et al., 2005). Willows and poplars in SRIC can be highly efficient for recycling organic residue from wastewater because of their remarkable growth rate (Labrecque and Teodorescu, 2001; Labrecque et al., 1998). Indeed, rapid biomass production is associated with a high nutrient turnover and an abundant use of water (Mirck, 2005).

Pollution and wastewater discharge are problems frequently encountered by fish farmers (Enell, 1995; Dumas et al., 1998; Naylor et al., 2003; Porrello et al., 2005). In raceway freshwater fish farms, the water flow rate is kept high to reduce free ammonia concentrations, which dilutes pollutants originating mostly from excreta and undigested fish food (Comeau et al., 2001). Handling a large volume of this type of water having a low concentration of pollutants requires special solutions (Jonsson et al., 2004). In the province of Quebec (Canada), the average flow rate of freshwater fish farms is 1600L/min with a mean phosphorus concentration of 0.3 mg/L (Ouellet, 1999). Therefore, extended water purification is appropriate for solving a water quality issue of such dimensions and the use of SRIC could represent a simple and cost-effective solution (Lowrance et al., 1984; Perttu and Kowalik, 1997; Licht and Isebrands, 2005).

Previous studies have shown that willow and poplar in SRIC use significantly more water than agricultural crops and other tree species (Grip et al., 1989; Hinckley et al., 1994; Lindroth et al., 1994) and are both characterized by an excellent capacity for acquiring nutrients under a variety of conditions and for tolerating waterlogging (Nixon et al., 2001).

In fact, high evapotranspiration rates decrease discharge flows toward natural waterways and increase water residence time, which facilitates nutrient absorption by roots (Hall et al., 1998; Pauliukonis and Schneider, 2001). Considering the large volume of water undergoing treatment, the high rate of water consumption of the selected trees can increase the purifying efficiency per surface unit of the plantation and ensure an optimal productivity for wood harvest. However, few studies conducted to date concern phosphorus retention capacity from diluted effluent. Also, the tolerance of willows and poplars to flooded conditions is specie-dependent (Hallgren, 1989; Good et al., 1992) and therefore the adaptation capacity of the selected species will influence the viability of the system.

The present study tested the hypothesis that intense irrigation of willow and poplar in SRIC could accommodate the high rate of flow characteristic of fish farm effluent and limit phosphorus discharge into natural ecosystems. The aims of the experiment were to analyze phosphorus purification efficiency and intense irrigation tolerance of a willow and a poplar species. Therefore, on a 400 m^2 experimental site, we (*i*) investigated growth and nutritional plant response to a high hydraulic regime of two different species (*Salix viminalis* and *Populus nigra x P. maximowiczii*) and (*ii*) evaluated the impact of a planted area on the levels of phosphorus in run-off.

MATERIAL AND METHOD

Site description

The experiment was conducted at a fish farm located in Chartierville (45°16′ N, 71°12′ W) in southern Quebec. This freshwater fish farm produces 50 tons of fish annually (*Salvelinus fontinalis* and *Oncorhynchus mykiss*), with an average water flow rate of 2213 L/min (Table 1.1). The climate of the region is continental humid, at an altitude of 550 m with an annual average temperature of 4.6°C and 1100 mm of precipitation. The length of the growing season varies between 120 and 140 days and total precipitation during this experiment (from June to September 2005) was approximately 320 mm (Environment Canada, 2005).

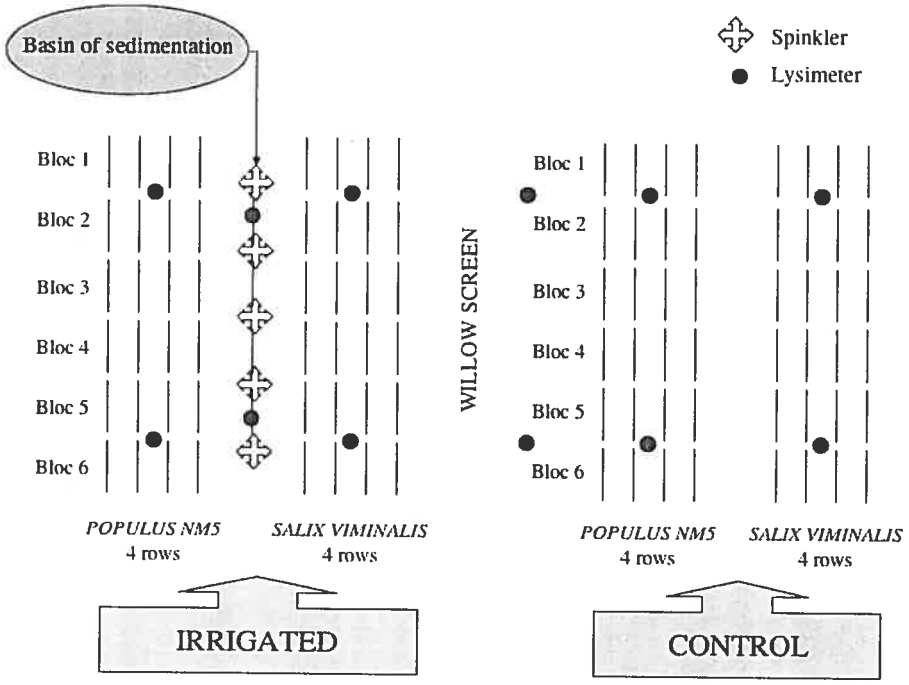
Table 1.1 Water characteristics measured from the effluent every two weeks in the sedimentation basin at the fish farm in Chartierville.

	Mg mg/L	Ca mg/L	NH_4 mg/L	K mg/L	NO_3 mg/L	P available mg/L	pH	Flow rate L/min
Mean	1.70	5.61	0.82	0.58	1.00	0.31	7.19	2213
Minimum	1.00	3.79	0.24	0.25	0.51	0.17	6.80	516
Maximum	2.26	7.30	1.74	1.58	1.95	0.45	7.87	5100

Species and experimental design

In the spring of 2004, soil was tilled on the 800 m^2 experimental site before adding a 30 cm layer of topsoil to homogenise the natural site and help provide good conditions for tree growth. One species of willow, *Salix viminalis* Mühl., and one hybrid poplar, *Populus nigra* x *P. maximowiczii,* were then planted, respectively codified by the ministère des Ressources naturelles et de la Faune du Québec as clone 5027 and clone 3729 (but also as clone NM5). *S. viminalis* has been successfully used in several SRIC plantations in southern Quebec over the last ten years (Labrecque and Teodorescu, 2003) and *Populus* NM5 has been identified as the most productive among ten willow and poplar species recently tested in an experimental trial (Labrecque and Teodorescu, 2005). A total of 1 200 cuttings were planted by hand every 20 cm, in 19 rows at a distance of 1.5 m apart and at a depth of 16-18 cm to create a plant density of 20,000 cuttings/ha. After one year of growth, the field was split into two plots (control *vs* irrigated) each composed with two subplots (*S. viminalis* and *Populus* NM5). Each subplot was separated into six blocks. Three meters separated the two species in each plot and six meters separated the control from the irrigated part. Within these six meters, three rows of *S. viminalis* were planted as a buffer to prevent irrigation water from reaching the control plot. Fish farm water was pumped from the sedimentation basin and sprinkled over the first plot (Figure 1.1). Irrigation occurred from June 22nd to September 13th 2005, 12 hours a day for a total of 148 mm of water per day, including the 4 mm/day that both plots received from precipitation during the experimental period. Regular weeding was performed by hand during the two growing seasons.

Figure 1.1 The experimental design of the 400m^2 plantation downstream from the fish farm at Chartierville.



In the spring of 2005, before the start of the irrigation treatment, 24 soil samples were taken at three different depths: 0-20, 20-40 and 40-60 cm (Table 1.2). The plantation site was a loamy-sandy texture with poor organic matter content (average around 1.7 % by mass). The pH of the soil was slightly acidic with an average of 6.3 over the three layers sampled. In the first 40 cm, the layer where roots expansion mainly occurs, the average content of N (1.1 mg/g) and P (1.5 mg/g) was low whereas content of K was considered high (17.0 mg/g) (Doucet, 1994). Soils samples were analysed colorimetrically on the flow injection instrument for P and N (Parkinson and Allen, 1975) while K, Mg and Ca were determined by using an atomic absorption spectrophotometer (Varian AA6™).

Table 1.2 Mean values of soil characteristics measured in samples taken at the Chartierville plantation in May 2005, before irrigation, at three different depths.

	0-20 cm	20-40 cm	40-60 cm
PH	6.1	6.5	6.3
Organic matter (% by mass)	1.5	1.2	2.5
Sand (%)	77.3	64.3	64.5
Silt (%)	17.4	28.3	28.9
Clay (%)	5.4	7.5	6.6
N mg/g	1.07	1.1	1.7
P mg/g (available)	1.52	1.5	1.8
K mg/g (available)	13.6	19.7	-
Ca mg/g (available)	3.5	4.7	-
Mg mg/g (available)	1.4	1.4	-

Water and nutrient application

The irrigation water pumped from the sedimentation basin of the fish farm was analysed every two weeks (Table 1.1). The proportion of all P forms was accomplished colorimetrically with the phosphomolybdenic complex in the presence of ascorbic acid (Murphy and Riley, 1962; Maher et al., 2002) and analysed by spectrophotometry. All water analyses were done under the supervision of Dr. Sébastien Sauvé at the chemical laboratory of University of Montreal. Nitrogen and phosphorus concentrations were rather constant throughout the season, even thou values from 3 to 4 times higher were observed in may with the melt of snow. Over the growth season, an average of 1.00 mg/L of NO_3, 0.82 mg/L of NH_4 and 0.31 mg/L of available P was measured. Based on these values and the amount of irrigation, the irrigated plot received a dose approximately equivalent to 220 Kg/ha of available N and 40 Kg/ha of available P over the experimental year. Ditches 1 to 2 meters deep surrounded the field experiment of the irrigated part.

Twelve lysimeters were installed at 1.5 to 2.5 meters in depth in each plot to collect infiltration water (Figure 1.1). The lysimeters were installed in the spring of 2004, one year prior to starting the irrigation treatment, to allow surrounding soil to stabilize. The

differences in depth were due to the stony subsoil, which made manual drilling of holes extremely difficult. During the irrigation period, the water retained by these lysimeters was sampled with a manual pump every two weeks (Table 1.3). Since the mean quantity of water sampled in each plot differed markedly, it is likely that water from the irrigated part did not flow in the non-irrigated part. Lysimeters situated in a treeless zone in each plot were used as a control value.

Measurements and analyses

All measurements were carried out among trees on the two middle rows of every block to limit the boundary effect. At the end of the growing season, in October 2005, growth and biomass partitioning were measured from eight plants randomly chosen in every block for each species and treatment, for a total of 192 plants. Height and diameter of the main stem were recorded while biomass, partitioned into leaves and stem, was collected and oven dried for 48 hours at 70°C.

In September 2005, samples from well-developed leaves 20 cm from the top of the shoots were randomly chosen in each block for tissue analyses. In October, samples of wood were also taken from different parts of 10 stems in each block. To analyse the nutrient content, samples of leaves and stems were dried, ground and then digested in sulphuric acid and peroxide with the addition of catalysts (lithium and selenium) at 340°C for about three hours. The digested solutions were analysed colorimetrically on the flow injection instrument for P and N (Parkinson and Allen, 1975) while K, Mg and Ca were determined from the sulphuric acid and peroxide digestion by using an atomic absorption spectrophotometer (Varian AA6™).

Analysis of variance (ANOVA) was used for comparing the above ground biomass of irrigated and control plots, as well as their nutrient content. Calculations were performed using Statistical Analyses Software (SAS Institute Inc, 2000) with a significance level of 0.05.

RESULTS AND DISCUSSION

Most experiments with flooding conditions reported in the literature use volumes of irrigation between 20 to 30 mm/day or simply the water level close to the soil surface (Hallgren, 1989; Good et al, 1992; Jonsson et al., 2004). In fact, the dosing of wastewater or sludge application is normally based on N-amounts since this strongly influences NO_3-N leaching loads (Elowson, 1999; Aronsson and Bergström, 2001). In this experiment, the very low concentrations of NO_3-N (1 mg/L) and available P (0,3 mg/L) did not require limiting the volume of wastewater provided to the plantation. By supplying 140 mm every day, the moderate doses of fertilizers applied (120 Kg of NO_3-N, 40 Kg of P_2O_5-P and 85 Kg of K_2O-K) were considered adequate for improving growth and reducing risk of leaching into loamy soil in regular hydraulic conditions (Labrecque et al., 1998; Aronsson and Bergström, 2001). The main stress factor encountered for the plantation was then the flooding conditions. During the irrigation period, accumulation of water on the soil surface rarely occurred for some blocks situated in small depressions. Water in blocs 1 and 2 for willows and blocks 3 and 4 for poplars (Figure 1.1) took more time to infiltrate the soil than elsewhere. Nevertheless, no block effect has been revealed by the statistical analysis for any of the variables.

Tree growth and flood tolerance

In spite of the fact that willows and poplars are well known for their tolerance to high water levels, intense irrigation can reduce air exchange in soil and negatively affect their biomass production (Elowson, 1999; Nixon, 2001). However, some authors have found that the response to these flooding conditions is species-dependent in *Salicaceae* (Hallgren, 1989; Liu and Dickmann, 1992). In this experiment, no mortality was observed, so the species did support the intense irrigation. For willows and poplars, there were no statistical differences for total biomass nor for stem biomass production between irrigated and control (Table 1.4). Also, no significant differences were found in the height and diameter of the main stem for both species. Therefore, even though the intense irrigation treatment was started early in the establishment of the plantation, at the beginning of the second growing season, both species seemed to have responded well to the extremely high level of irrigation.

A significantly lower foliar biomass for irrigated trees was measured for *P.* NM5 (p=0.003) (Table 1.4). In a similar study, Liu and Dickmann (1992) reported analogous observations concerning reduced leaf expansion of certain *Populus* species under flooded conditions. Good et al. (1992) neither found any significant effect of waterlogging in relation to leaf dry weight parameter for *S. viminalis*. This indicates that the transpiration potential of *P.* NM5 could be reduced under intense irrigation contrary to *S. viminalis*, even though poplars usually have a transpiration rate slightly superior to that of willows (Persson and Lindroth, 1994; Hall et al., 1998). With the objective of purifying a large volume of water, the potential of evapotranspiration is an important factor.

Table 1.4 Leaves and stems average dry mass (g) per plant for non-irrigated (control) and irrigated *P.* NM5 and *S. viminalis*.
NOTE : Values with * are different for Control and Irrigated plot at p < 0,05.

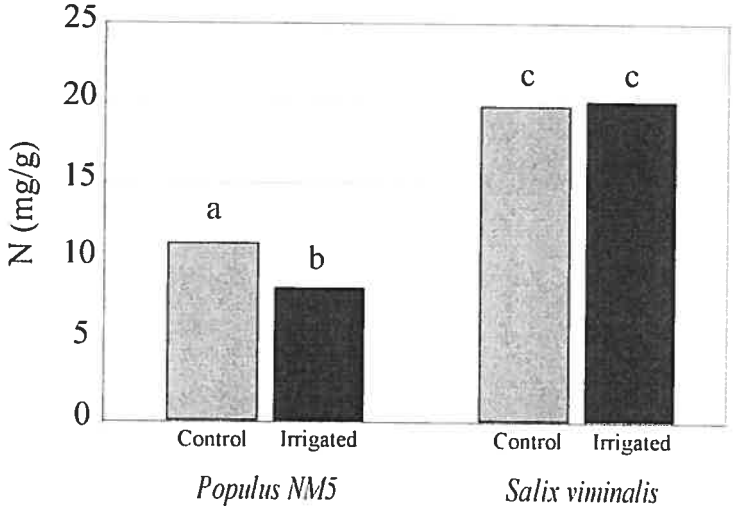
		CONTROL	IRRIGATED
Populus NM5	Leaves *	18.5	10.4
	Stems	36.8	36.9
	Total	55.3	47.3
S. viminalis	Leaves	9.9	9.8
	Stems	36.4	38.6
	Total	46.3	48.4

In order to evaluate the ability of these species to withstand the effects of waterlogging, the nutritional status of the trees in both plots was analysed. The nutritional status of plants can be characterized by the concentration of N and the ratios of macro-elements contained in the leaves. For *P.* NM5, N leaf concentrations were under the level for sufficient growth of 17 mgN/g as suggested by van den Burg (1990). The leaf samples from the irrigated plots showed a mean concentration of 8.3 mgN/g compared to 11.0 mgN/g in the control (p=0.016) (Figure 1.2). Soil water status significantly alters the utilization of soil N (Liu and Dickmann, 1992; Pezeshki et al., 1999). Nitrogen deficiency symptoms such as a loss of green colour progressing to yellow coloration were moreover visible starting from the middle of the summer for irrigated poplars. Salix showed concentrations of N in leaves of 20 mgN/g in both plots, as reported by Labrecque et al. (1998) for willows cultivated in

unfertilised plantations. These results are very close to the critical value for sufficient growth of 21 mgN/g for *Salix* species according to Kopinga and van den Burg (1995).

The macronutrient ratios in the leaves were calculated with respect to N. For deciduous trees, these ratios are considered optimal at these levels: N = 100, P = 10-14, K = 50-100, Mg = 10 (Kopinga and van den Burg, 1995). In this experiment, all ratios for *P.* NM5 exceeded these optimal values, especially for the irrigated plot since these values were significantly higher for P, K and Ca compared to control values (Table 1.5). With a deficiency in N concentration and high ratios of other elements, *P.* NM5 showed a significant nutritional imbalance, which suggests a limited longevity potential for trees. As a matter of fact, *P.* NM5 also presented a low biomass yield (1 tDM/ha) (Table 1.4), compared to the 20tDM/ha harvested after two years of growth for the exact same specie by Labrecque et al (2005). Since this unsatisfactory growth was also observed in the non-irrigated plot, field conditions and the limited length of the vegetation growth period could be factors responsible for this weak biomass production. However, before one can hope to draw benefits from water filtration in terms of biomass productivity, the sustainability of the filtration system must be assured through the physiological aptitude of species to respond to flood conditions.

Figure 1.2 Average N foliar concentrations of irrigated and non-irrigated (control) plants of *P.* NM5 and *S. viminalis*.
NOTE : Columns with different letters are significantly different (p< 0,05).



Studies carried out on a site where nutrient levels did not limit birch tree growth (*Betula pendula* Roth), which have a comparable nutritional behaviour to willows (Ericsson et al., 1992), demonstrated that foliar macronutrient ratios with respect to N=100 were >8 for P (Ericsson and Ingested 1988), >23 for K (Ericsson and Kahr, 1993), and >1 and >4 for Ca and Mg, respectively (Rytter and Ericsson 1993). In this experiment, ratios calculated for *S. viminalis* were in the upper limit of these ranges, except for P (ratio of 6) in the irrigated trees (Table 1.5). As mentioned before, high water level in soil can decrease absorption of macronutrients because of reduced root activity (Kozlowski, 1997; Licht and Isebrands, 2005). We therefore observed a low concentration of P in the irrigated leaves of *S. viminalis* although the P removal capacity is not altered by the irrigation since there were no significant differences for stem's P concentration (results not shown). Considering that in a short rotation woody crop system, harvest usually takes place in winter and leaf content returns to the soil through litter, the crop's nutrient absorption capacity depends largely on stem content. *S. viminalis* is normally known for its impressive growth, but the field conditions of this experiment do not justify a comparison of productivity with the average obtained in other studies on agricultural sites. The dry biomass yields reached in this experiment after two years of growth (1 tDM/ha) are slightly under the values reported for this specie in southern Quebec in non-fertilized conditions (2 tDM/ha) (Labrecque and Teodorescu, 2001; Labrecque and Teodorescu, 2005). Also, yield of willow plantations in SRIC can increase considerably during a second rotation, by about 44 to 300% in comparison to the first rotation cycle (Jug et al., 1999). Therefore, retention capacity could probably reach higher values after the first rotation cycle, since this specie seems to satisfy its nutritional needs even under intense irrigation and poor soil conditions.

Table 1.5 Ratios of the nutrient contents in foliar tissues of irrigated and non-irrigated (control) plants for *P.* NM5 and *S. viminalis* (N considered to be 100 part).

		P	K	Ca	Mg	K/Ca	K/Mg
Populus NM5	CONTROL	17*	248*	100*	22	2.5	11.5
	IRRIGATED	11	166	116	19	1.4	8.6
***Populus* sufficient growth values**		**10-14**	**50-100**	**-**	**10**	**1-3.5**	**1-9**
S. viminalis	CONTROL	9	130	50*	15	2.6	8.8
	IRRIGATED	6	116	25	9,8	4.6	11.5
***Salix* sufficient growth values**		**8**	**23**	**1**	**4**	**1.3-2.5**	**3-8.5**

NOTE: Values with * are different for Control and Irrigated plot at $p < 0,05$. *Populus* sufficient growth values are from Kopinga and van den Burg, 1995. *Salix* sufficient growth values of N and P are from Ericsson and Ingested 1988, of K from Ericsson and Kahr, 1993 and of Ca and Mg from Rytter and Ericsson,1993.

Treatment efficiency

The plant-soil system used in this experiment could absorb the total volume of water applied on the plantation since no surface run-off was observed. According to our observations, tree growth seems to have reduced NO_3 leaching even though high irrigation increases the risk of N leaching (Jonsson et al., 2006). Only samples from lysimeters of the irrigated area, where no trees had been planted, showed presence of NO_3 in the drainage water (Table 1.3). However, lateral drainage may have occurred in sub-surface layers, since the concentrations of NH_4 collected in lysimeters from the irrigated plot were 10 to 15 times lower than in the control area (Table 1.3). On the other hand, this significant decrease in NH_4 concentration may also be explained by a dilution caused by irrigation water. P was below detection levels of 0,01 mg/L in all lysimeters. In a similar study with intense irrigation (50 mm/day) and higher concentration of P (1 mg/L), Jonsson et al. (2006) also reported P retention levels as high as 96%.

Table 1.3 Mean values of water analysis sampled in lysimeters every two weeks throughout the irrigation period of summer 2005 at Chartierville.

		Volume of water ml	NH_4 mg/L	NO_3 mg/L	P mg/L
CONTROL	*Populus* NM5	208	7.7	0	0
	S. viminalis	167	9.3	0.1	0
	No tree	695	8.2	0	0
IRRIGATED	*Populus* NM5	612	0.8	0	0
	S. viminalis	1359	2.3	0	0
	No tree	942	0.4	0.5	0

By providing 140 mm per day to this 400m^2 plantation surface, approximately 4% of the fish farm effluent was treated. Total P removals over this experimental surface via shoot biomass for *S. viminalis* and *P.* NM5 was estimated at 0.5-1 Kg P while approximately 1 to 1.5 Kg P was brought up with the irrigation. This P removal capacity could be considered quite low (approximately 66%), but it is important to mention that in the current experiment, plants had not reached maturity before intense irrigation started. In other environmental conditions, the purification efficiency of these species at maturity and without fertilisation over a four-year growth period can be up to 12 Kg P /ha per year (Labrecque and Teodorescu, 2005). In Quebec, the aim of the Environment Ministry is to reduce the P emissions from fish farms by 40%. According to our results, we evaluate that a surface of 1 hectare could be sufficient to filter 100% of the effluent with a partial P retention (66%) with possibility of P accumulation in soils. Reducing the irrigation by half could help to reach a complete retention using 2 hectares. The use of arbuscular mycorrhizal fungi to increase P removal could also be considered in this context (Jones et al., 1991; Baum and Makeschin, 2000). According to these previous studies, the benefits related to mycorrhizal infection on plant growth and P uptake is superior under low P concentrations. More efficient P removal from plant biomass would allow for a smaller plantation size.

CONCLUSION

In general, *P.* NM5 and *S. viminalis* showed tolerance to flooding as evidenced by the lack of mortality. However, to ensure the performance of the filtration system, prior consideration should be given to the specie that offers the best yields, for a higher evapotranspiration potential and a more significant total nutrient removal. Given the conditions of this study, *S. viminalis* seems to promise better longterm purification efficiency since this specie has met its nutritional needs more effectively and reached the average year growth while preserving an equivalent foliar biomass even under intense irrigation. However, these results cannot be extrapolated to several irrigation seasons without further studies. When the hydraulic rate of an effluent is not balanced with the rate of uptake of water and nutrients by the crop concerned, problems can develop with build-up of salinity and pollutants or contamination of groundwater. For this reason, selecting the most suitable specie for the site location and climate or experiencing the benefits of mycorrhizal colonisation to facilitate nutrient absorption could be interesting avenues for other studies.

Acknowledgements

We extend special thanks to Jérémy Locklear, Marie-Josée Tardif and Hélène Lalande for fieldwork and technical support. The authors would also like to express their sincere appreciation to Pierre Vézina, the owner of the fish farm, for the space provided for this experiment and his precious colaboration. This experiment was funded by the Fonds québécois de la recherche sur la nature et les technologies (FQRNT).

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- **Chapitre 3.**

PHOSPHORUS RETENTION EFFICIENCY OF ONE HYBRID POPLAR AND TWO WILLOW SPECIES USING ARBUSCULAR MYCORRHIZAL FUNGI

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Abstract — Using mycorrhizal fungus for phytoremediation strategies offers viable opportunities to increase biomass productivity and hence improve pollutant uptake. In this study, *Populus* NM5 *(P. nigra* vs. *P. maximowiczii), Salix miyabeana* (SX64) and *Salix viminalis* (5027) were planted in pots to evaluate the influence of colonisation by fungi *Glomus intraradices* on phosphorus uptake after one year of growth using two different phosphorus concentrations in irrigation water. Based on analysis of the foliar and woody components, our results show that the two treatments (mycorrhizas and P-irrigation) interact differently with total P content. The foliar P content is principally enhanced by the P-irrigation concentration, whereas the mycorrhizal colonisation increases stem P content. The latter increase is mainly due to an increment of biomass production, without modification of the P concentration, indicating that mycorrhizal associations affect the phosphorus use efficiency. *G. intraradices* increased total biomass of *S. miyabeana* and *S. viminalis* which consequently increased their P content in stems by 33%. Colonisation on *P.* NM5 resulted in an increase of the main stem height throughout the year of study, but had no effect on total biomass or on total P content.

INTRODUCTION

In Canada, most lakes adjacent to agricultural lands present eutrophication. Phosphorus leaching into surface waters from fish farming sources has been identified as a contributor to surface water quality degradation (Ouellet, 1999). For this industry to remain sustainable, phosphorus discharge must be reduced, but handling large volumes of water with a low concentration of pollutants requires special solutions (Jonsson and al., 2004).

Large-scale water purification techniques may improve water quality, and the use of a vegetation filter could represent a simple alternative as well as a cost-effective solution (Lowrance et al., 1984; Perttu and Kowalik, 1997; Licht and Isebrands, 2005).

For many years now, vegetation filter efficiency has been demonstrated in several countries by field lysimeter and full-scale experiments (Perttu and Kowalik, 1997; Nixon et al., 2001; Mirck et al., 2005). As a matter of fact, poplars (*Populus spp.*) and willows (*Salix spp.*) have been used for riparian plantings for centuries (Lowrance et al., 1984; Licht and Isebrands, 2005), and they are still the most common tree species used for wastewater filtration because of their rapid biomass production, which causes a high nutrient turnover and makes abundant use of water (Mirck et al., 2005). The filtration process takes advantage of this potential of plants to use water and nutrients. Plant filtration also offers interesting economic opportunities for short rotation forestry, since the irrigation of a plantation with landfill leachate reduces water stress for trees and supplies constant fertilization, thus promoting tree growth (Nixon et al, 2001).

Mycorrhizal associations are also known to have positive effects on plant growth (Jones et al., 1990; Baum and Makeschin, 2000). In addition to stimulating performance and development, mycorrhizal fungi can increase winter survival and pathogen resistance (Van der Heijden, 2001; Khasa et al., 2002). In fact, the benefits of mycorrhizas to host plants are multiple, but their major impact on productivity is associated with an increased supply of phosphorus to the plant via the mycorrhizal hyphea (Khasa et al., 2002). In a phosphorus limiting environment, arbuscular mycorrhizal fungi (AMF) predominate over ectomycorrhiza (Van der Heijden and Kuyper, 2001). The prospect of using AMF inoculums for P filtration at low concentrations is consequently interesting. Yet relatively little is known about mycorrhizal impact in phytoremediation strategies with organic pollutants and few studies have examined the colonisation of *Populus* and *Salix* species using commercial inoculums.

The aim of this experiment was to determine the impact of AMF colonisation on the performance of three species in terms of P uptake. In a pot trial, we compared the

phosphorus retention efficiency of two species of willow and one hybrid poplar presenting a good potential for use as commercial biomass energy crops in southern Quebec (Canada); *Salix viminalis*, *Salix miyabeana* and *Populus* NM5 *(P. nigra* vs. *P. maximowiczii)*. Throughout this experiment, the benefits of AMF colonisation on productivity and total P content have been evaluated for the selected species. Our objective was to verify the efficiency of the symbiosis for wastewater filtration strategies using diluted effluents, containing two different P concentrations in the irrigation water, one approaching a fish farm effluent concentration, 0.5 mg/L and another one 20 times more concentrated (10 mg/L) as a basis for comparison.

MATERIAL AND METHOD

Experimental design

The study was designed as a multifactor experiment including four blocks, three species, treatment with and without mycorrhizal, and two irrigation treatments (0.5 mg/L and 10 mg/L of P). Three plants were grown for each specie, as well as for each mycorrhizal and irrigation treatment, for a total of 144 plants. In February 2005, cuttings of *S. viminalis*, *S. miyabeana* and *P.* NM5 20 cm in length were planted individually in 2-litre plastic pots. Half of the 144 plants were inoculated with *Glomus intraradices* at 3% volume mixed with a peat-based growing medium with vermiculite and perlite (Promix BX 0431). *G. intraradices* is the endomycorrhiza most frequently used as a commercial inoculum. Geographically distributed all over the world, it can colonize a large variety of host plants and survive long-term storage (Dalpé and Monreal, 2004). To enable better colonisation by the mycorrhiza, we used a soil with available P inferior to 10 mg/m^3. For three months, plants were grown in a partial split plot at the Montreal Botanical Garden under greenhouse conditions: temperature of 22±2 °C, natural light conditions and irrigation provided every two or three days. Mycorrhized plants were separated from the non-mycorrhized to reduce the possibility of contamination.

In May, plants were coppiced to control plant transpiration in the greenhouse and the biomass harvested was recorded. Three weeks later (at the end of May), plants were transplanted into 20-litre plastic pots using the same cultured soil mix without new *G. intraradices* inoculants and moved outside following the same design than in the greenhouse. Twice a week, half of the plants were irrigated with two litres of a sodium phosphate solution (Na_2HPO_4-$7H_2O$) at a concentration of 0.5 mg P/L and the other half with the same solution at a concentration of 10 mg P/L. To balance amendment, 5 g of ammonium nitrate and 3 g of sulphate potassium (equivalent of 100 Kg N/ha and 60 Kg K/ha per year) were added to the pots (half a dose in may and the other half in july).

Measurements and analyses

Beginning two weeks after the plants were brought outside (during the first week of June) and every two weeks subsequently until the end of the study, plant growth was monitored by measuring the diameter at the base and the height of the main stem of all plants. In mid-August, samples of leaves were randomly collected from each individual (5 leaves for *Populus* and 15 for *Salix*) to calculate the specific leaf area (SLA). The surface area was determined with a leaf-surface-area meter (MK2 Delta-T Devices; Cambridge, England) and the dry mass was obtained after 48 hours drying in an oven at 70°C. The ratio of these two values equals the SLA, used to calculate the total leaf area of each plant.

In mid-October, the plants were harvested and separated into roots, stems and branches, and leaves. These three sampling groups were oven-dried at 70°C for 48 hours and then weighed. Subsamples from wood and roots, but also from leaves collected in August were ground up for tissues analyses. To determine the nutrient content of these samples, the organic tissues were digested in sulphuric acid and peroxide with the addition of catalysts (lithium and selenium) at 340°C for about three hours (Parkinson and Allen, 1975). The digested solutions were analysed colorimetrically on the flow injection instrument for P and N while K, Mg and Ca were determined from the sulphuric acid and peroxide digestion by using an atomic absorption spectrophotometer (Varian AA6™).

Mycorrhizal colonisation (%) was calculated using the staining technique proposed by Horst (1998). After the harvest, 6 g (fresh weight) of fine roots were collected from one plant of every treatment combination in each of the four blocks, for a total of 48 randomly selected plants. Roots were washed carefully and stored in a 50% alcohol solution for conservation. For each root sampling unit, a random subsample of approximately 300 cm total root length was cleared by boiling 1 hr at 95°C in 10% KOH. Cleared roots were soaked overnight in a 5% ink-vinegar solution with pure white household vinegar (5% acetic acid). Roots were distained by rinsing in tap water and kept in a slightly acidified solution. Assessment of colonisation after clearing and staining was performed according to the gridline intersect method (Brundrett et al., 1996), designed to quantify intersection points of roots and grid lines, which are classified either as colonized or non-colonized.

Analyses of variance (three-way ANOVA) were used to determine the effect of treatments (P and myco) on growth, productivity, nutrient content and total leaf area. The calculations were performed using Statistical Analyses Software (SAS Institute Inc, 2000) with a significance level of 0.05.

RESULTS

Mycorrhizal Colonisation

No AMF colonisation was observed on roots of non-inoculated plant samples (Table 2.1). *P.* NM5 presented the highest percentages of colonisation in inoculated samples and a significant difference was observed according to the concentration of P in the irrigation water used (29% with the 0.5 mg/L P irrigation and 15% with the 10mg/L). In both willow species, the percentage of mychorrizal colonisation was superior when plants were irrigated with 10mg/L of P (Table 2.1).

Growth

At the beginning of plant height measurements, mycorrhized plants presented greater main stem heights with a p=0.03 until day 40 (Figure 2.1). For *Salix* species, this slight advance tends to diminish throughout the season; from day 20 for *S. viminalis* and day 60 for *S. miyabeana*. Mycorrhized plants of *P.* NM5 maintain this growth advance on non-mycorrhized plants all summer long, but present an equal growth rate. For all three species, the P concentration in the irrigation water did not induce any plant height modification over the course of this experiment.

Table 2.1 Percentages of AMF root length colonisation of the three species at two levels of P irrigation.

Specie	P irrigation (mg/L)	Inoculation -	Inoculation +	
Populus NM5	0.5	0%	29% a	X
	10	0%	15% b	
Salix miyabeana	0.5	0%	5% a	Y
	10	0%	13% b	
Salix viminalis	0.5	0%	6% a	Y
	10	0%	11% b	

NOTE : Means within rows followed by different letters are significantly different ($p < 0.05$).

Productivity

Mycorrhizas significantly increase biomass production of both *Salix* species, inducing an individual increment of 20g to 60g on total dry mass (p=0.013) (Table 2.2). The P concentration in the irrigation water had no effect on biomass production for all species, nor on the total leaf area. Additionally, the total leaf area shows very little variation among the different treatment combinations.

The calculation of the root/shoot ratio helped to evaluate the resource availability throughout the growth season. There are no significant changes for this ratio across the

different treatments (Table 2.2). However, the ratio tended to decrease slightly in the presence of mycorrhizas for *S. miyabeana*. Therefore, non-mycorrhized plants may have been more subject to nutritional stress than mycorrhized plants, investing more in root development.

Figure 2.1 Average growth curves for *Populus* NM5, *S. miyabeana* and *S. viminalis* under two P irrigation levels and with or without mycorrhizal inoculum, from June 5th (day 1) to September 13th, 2005 (day 100).

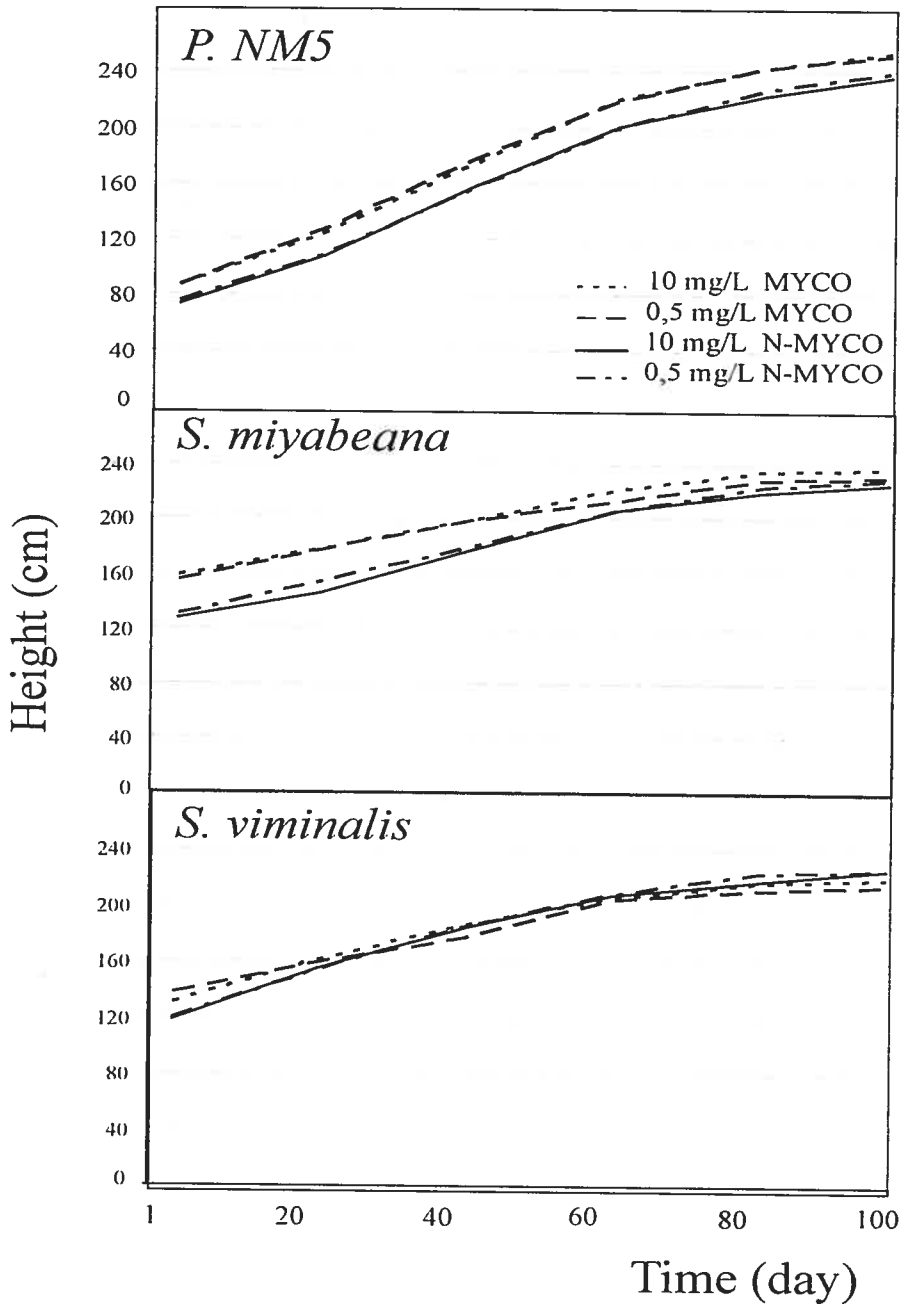


Table 2.2 Indexes of productivity (dry mass) and resource use efficiency (root/shoot ratio and specific leaf area) for each specie.

Species	Indexes	P irrigation	Inoculum	
		mg/L	-	+
P. NM5	DM	0,5	224	242
		10	222	232
	R/S	0,5	0.41	0.37
		10	0.51	0.51
	Total leaf area	0,5	0.85	0.83
		10	0.80	0.79
S. miyabeana	DM *	0,5	268	301
		10	241	301
	R/S	0,5	0.57	0.43
		10	0.51	0.39
	Total leaf area	0,5	0.68	0.71
		10	0.66	0.72
S. viminalis	DM *	0,5	251	270
		10	257	273
	R/S	0,5	0.53	0.55
		10	0.55	0.50
	Total leaf area	0,5	0.48	0.47
		10	0.49	0.50

NOTE: DM = total dry mass (g); R/S = root/shoot ratio; Total leaf area = m^2
Indexes with * present values different at $p < 0.05$ for the inoculation treatment.

Phosphorus concentration and content

For this experiment, the calculation of nutrient concentration is expressed in mg of P per g of dry mass whereas the calculation of nutrient content involves both measures, concentration and biomass, and is expressed in mg of P. The P irrigation of 10 mg/L significantly increased the P concentration in foliar tissues of all species ($p=0.002$) (Figure 2.2). Therefore, the impact of the P irrigation is significant on foliar P content compared to mycorrhization. Since no interaction was observed between both treatments (P irrigation and mycorrhization), the percentage of increase conceded to each treatment on the P content for leaves and stems separately was calculated in Table 2.3. The foliar P content of *P.* NM5, *S. miyabeana* and *S. viminalis* is respectively enhanced by 44%, 18% and 38%

with increasing P irrigation and by 1%, 13% and 6% with a mycorrhization treatment (Table 2.3).

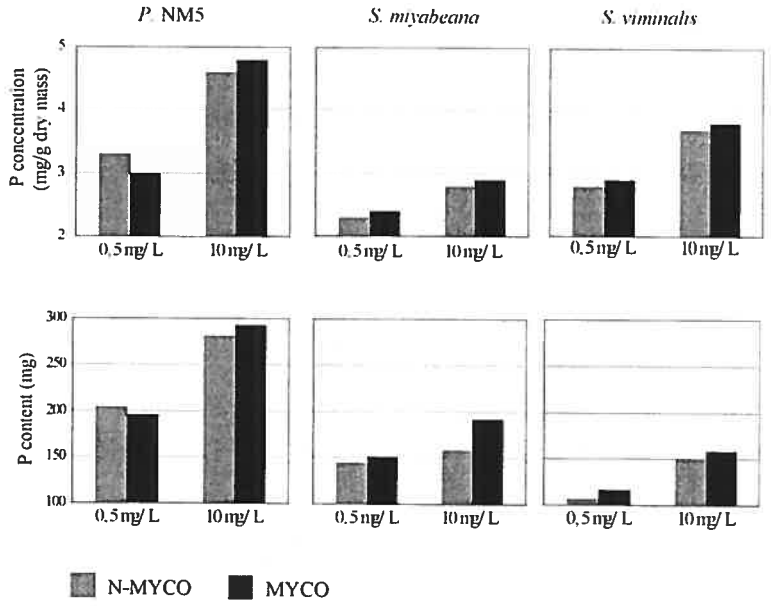
Neither mycorrhization nor P irrigation have any significant effect on stem P concentration (Figure 2.3). However, mycorrhizal colonisation has a great impact on P content in stems, especially for *S. miyabeana*, since this treatment significantly increased the woody biomass. In Table 2.3, both *Salix* species show an increase of 33% in stem P content under mycorrhizal treatment, compared to a gain of 7% and 2% under P irrigation.

Table 2.3 Percentage of increase of plant P content in leaves and stems with increasing P irrigation and mycorrhizal colonisation.

		LEAVES	STEMS
P. NM5	Irrigation	44 %	12 %
	Mycorrhization	1 %	9 %
S. miyabeana	Irrigation	18 %	7 %
	Mycorrhization	13 %	33 %
S. viminalis	Irrigation	38 %	2 %
	Mycorrhization	6 %	33 %

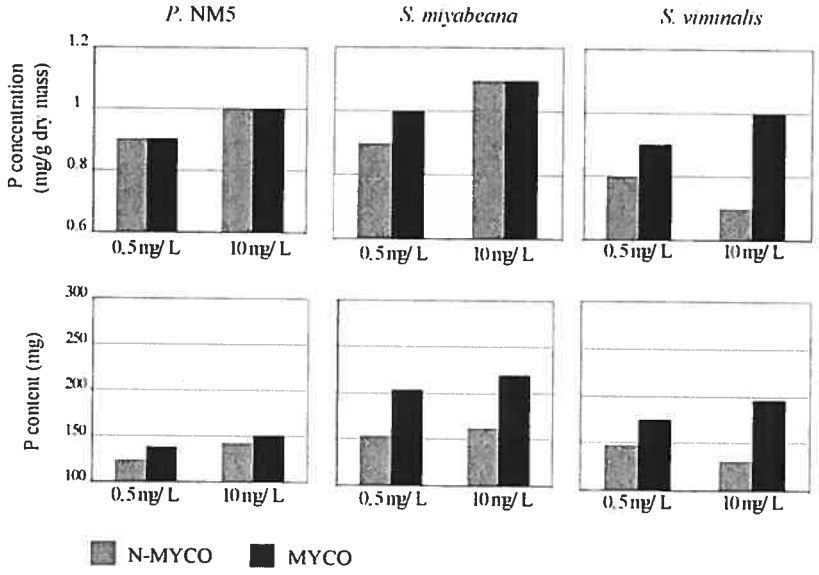
NOTE: p values for Leaves : P Irrigation p=0.03 and Mycorrhization p=0.88
p values for Stems : P Irrigation p=0.10 and Mycorrhization p=0.03

Figure 2.2 Leaves phosphorus concentration (mg/g of dry mass) and phosphorus content (mg) of *Populus* NM5, *S. miyabeana* and *S. viminalis*.



NOTE: p values for leaves P concentration: P Irrigation p=0.017 and Mycorrhization p=0.89
p values for leaves P content : P Irrigation p=0.03 and Mycorrhization p=0.88

Figure 2.3 Stems phosphorus concentration (mg/g of dry mass) and content (mg) in *Populus* NM5, *S. miyabeana* and *S. viminalis*.



NOTE: p values for stems P concentration: P Irrigation p=0.20 and Mycorrhization p=0.21
p values for stems P content : P Irrigation p=0.10 and Mycorrhization p=0.03

DISCUSSION

Mycorrhizal colonisation

Glomus intraradices occupies very wide ranges of hosts and ecosystems and as a symbiont, is highly effective in stimulating plant growth (Martin et al., 2004). In this study, fungi *G. intraradices* had a positive impact on productivity of colonized willows and poplars. According to our results, the benefit of the mycorrhiza seems more significant for *Salix* species even though the levels of colonisation were lower than in *Populus*. This observation concurs with other studies where low root colonisation did not necessarily imply weak plant response. For instance, increased plant growth was observed at very low colonisation by AM fungi with *Salix repens* (less than 5% colonisation) (van der Heijden, 2001; van der Heijden and Kuyper, 2001) and *Atriplex nummularia* (1-2 % colonisation) (Asghari et al., 2005). In general, poplars also present higher ectomycorrhizal colonisation indices than willows (Baum and Makeschin, 1997). Nevertheless, biomass production never seems correlated to percent of colonisation in the present study. It is important to note that the origin of the colonisation observed here in this study cannot be entirely confirmed as a result of the initial inoculation with *G. intraradices*. Analysis of the colonisation level was done on the basis of *G. intraradices*'s morphological characteristics.

It is known that N or P fertilization reduces root colonisation by mycorrhizas (Jones et al., 1990; Baum et al., 2002). This predictable inhibition of fungal colonisation caused by an increase of available P was observed in our study with *P.* NM5. The opposite phenomenon occurred with *S. miyabeana* and *S. viminalis*, which increased their colonisation rate under higher P-fertilization. According to Baum (2002), fertilizers can cause different responses in mycorrhizal formation by *S. viminalis* under different site conditions (soil type, climate, number of applications, irrigation). Although responses to mycorrhization are not correlated to the degree of colonisation, AMF are nevertheless known to be highly effective in mobilizing, taking up and transferring mineral nutrients from soils to plants under poor P conditions (Khasa et al., 2002). It is therefore interesting to note that, in this experiment, the response to mycorrhization was never influenced by the P-irrigation treatment. No interaction was observed between the two treatments (mycorrhization and P-irrigation) in

the statistical analyses (p>0,05). Our results suggest a large spectrum of action for *G. intraradices* in association with willow and poplar species.

Productivity

The growth curves in Figure 2.1 show the benefits offered by mycorrhizas on plant growth. The observation of a similar growth rate between mycorrhized and non-mycorrhized plants for *P.* NM5 suggests that this association is profitable in early developmental stages. Van den Heijden (2001) also found that the influence of AMF was observed principally during the first five months of plant growth. Small differences in plant size in the earliest phases of growth can make a lasting difference since asymmetric competition can lead to large differences in success (Koive, 2000). In this experiment, the limiting conditions of a pot trial may also be the factor responsible for the tendency toward decreasing differences between the various treatments over the course of the season for *Salix* species.

AMF colonisation caused a significant increase of the total dry mass (p=0.013), especially for *S. viminalis* and *S. miyabeana*. These results attest to the effectiveness of the *G. intraradices* inoculums in the increase of biomass production, much as has been previously found by other authors with different AM fungi (Jones et al., 1990; Baum et al., 2002). It should be noted that this increase in biomass is observed even though the total leaf area values do not vary between the treatments. This could indicate that mycorrhizal associations may affect nutrient absorption but not photosynthetic activity.

In response to low nutrient availability, plants tend to increase the allocation of assimilates to their roots, thus enabling them to exploit a larger volume of soil (Van der Heijden, 2001; Mant et al., 2003). In this experiment, although a significant increase in biomass was measured under mycorrhizal colonisation, no variation of the root/shoot ratio was observed as a result of this treatment. This may indicate that mycorrhizas increase nutrient availability for the plant and stimulate biomass productivity by increasing root extension. On the other hand, no significant variation was observed for the root/shoot ratio, or for the total biomass between the two P irrigation concentrations. The lower concentration of P

(0.5 mg/L) was either still sufficient to enable regular growth, with no need for root expansion, or else other nutrients could have become a limiting factor for all plants, restraining root growth. However, if we consider the example of *S. miyabeana*, which presented a slight reduction of the root:shoot ratio in the presence of the inoculum, we cannot ignore the possibility that the limiting conditions of a pot trial may also have affected root expansion in some cases.

Nutrient content

Plant's nutritional status helps us to understand the nature of the influence of mycorrhizas versus P-fertilization. Based on the analysis of the foliar and stem tissues, our results show that the two treatments (P-irrigation and mycorrhization) act differently with the total P content. In this study, the increment of P-irrigation significantly increased foliar P concentrations while the mycorrhizal treatment had no effect on this value. On the other hand, P concentration in stems was not affected by any treatment. Nevertheless, mycorrhization indirectly increased the stem's P content due to its substantial impact on biomass production. In the stem tissues, the P content was increased by 33% for *Salix* species under the mycorrhizal treatment. Considering that in a short rotation woody crop system, harvest usually takes place in winter and leaves content is returned to the soil through litter. Therefore, the crop's nutrient absorption capacity depends largely on stem content.

CONCLUSION

Few studies have been done on the AMF inoculation of *Populus* and *Salix* species. Using mycorrhizas for phytoremediation strategies is an alternative that seems to offer promising advantages. The association with inoculums considerably improves the absorption of nutrients thereby stimulating plant growth. According to our results and previous studies, the inoculum's effectiveness is specie dependent. Under our trial conditions, the use of *G. intraradices* seemed more profitable to willows than poplars, and especially to *S.*

miyabeana. With the objective of using mycorrhizas for P filtration in fish farm effluents, the influence of the level of irrigation on colonisation should be subjected to further analysis. It would also be interesting to study the additional effect of natural mycorrhizas on the commercial inoculums used in this study.

Acknowledgements

The authors are very grateful to Traian Ion Teodorescu and Marc Saint-Arnaud from the Institut de recherche en biologie végétale for their scientific comments. We also wish to express our appreciation to Gabriel Teodorescu, Jérémy Lockwell and Hélène Lalande for fieldwork and technical support, and to the Montreal Botanical Garden for the space provided in greenhouses and nursery. A special thanks to Premier tech for providing the inoculums used in this experiment.

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- **Chapitre 4. CONCLUSION**

Ce travail avait pour but de démontrer l'efficacité d'espèces de saule et de peuplier pour le traitement d'effluents peu concentrés en mode d'irrigation intensive. Cette problématique a été abordée en planifiant deux phases d'étude, l'une réalisée en conditions naturelles, l'autre en conditions semi contrôlées.

En utilisant une plantation à haute densité, sur le modèle des cultures intensives sur courtes rotations (CICR), la réponse des plantes a été suivie durant une saison de croissance. L'intérêt était de vérifier l'impact des conditions physico-chimiques engendrées par une forte irrigation sur le développement des plantes, de même que sur leur capacité à retenir le phosphore en milieu naturel. L'étude réalisée en conditions semi contrôlées impliquait entre autre l'ajout d'un inoculum commercial (MYCORISE®, Premier Tech) de mycorhize arbusculaire, *Glomus intraradices*. Ici l'objectif principal était de vérifier si, de cette manière, l'absorption du P pouvait être accrue.

L'étude en milieu naturel conduite à la pisciculture de Chartierville a démontré que l'exploitation d'une culture intensive d'arbres à croissance rapide était une technologie qui pouvait contribuer au processus de réduction des émissions de phosphore des effluents piscicoles à fort débit. De façon générale, *Populus* NM5 et *Salix viminalis* ont révélé une bonne tolérance aux conditions d'inondation par une absence de mortalité parmi les plants irrigués et une biomasse comparable entre ces derniers et les plants témoins. Toutefois, pour assurer une plus grande efficacité à ce mode de filtration, une considération particulière devrait être accordée aux taxons qui présente la plus grande tolérance aux conditions engendrées par l'irrigation intensive, une contrainte qui découle de la gestion d'un effluent à fort débit.

L'évaluation de l'état nutritionnel des arbres nous a permis de mieux juger de la vigueur des arbres testés suite au traitement d'irrigation. Le statut nutritionnel de *S. viminalis* a semblé moins affecté par les conditions imposées (concentration foliaire de 20 mg N/g)

comparativement à *Populus* NM5 qui a montré des signes de déficience nutritionnelle très tôt en saison (concentration foliaire de 10 mg N/g). Du point de vue de la biomasse, les deux espèces ont présenté une faible productivité avec ou sans irrigation, soit 1tDM/ha deux ans après leur mise en terre. Il est cependant à noter que les conditions de croissance dans le cadre de cette étude ne permettent pas de comparer ces taux de productivité à ceux qu'il est possible d'obtenir en milieu agricole avec les mêmes espèces, soit entre 10 et 20 tDM/ha après deux années de croissance (Jug et al., 1999; Labrecque et Teodorescu, 2005).

La capacité de rétention du phosphore pour les deux espèces a été évaluée à des valeurs comprises entre 0,5 et 1 Kg P/ha par année. Il faut ici aussi considérer que dans cette région du Québec, les saisons de croissance sont plus courtes que celles de la région de Montréal où la majorité des CICR de saules et de peupliers ont été établies et étudiées. Par ailleurs, il est possible que le fait d'avoir débuté l'irrigation très tôt suivant l'établissement des plantes (un an après la plantation des boutures dans des conditions de croissance difficile) ne constitue pas la situation idéale. Il aurait sans doute été préférable que le traitement d'irrigation s'amorce lorsque les plants sont bien enracinés, après deux ou même trois saisons de croissance. Il est probable que des plants mieux établis avec un système racinaire plus développé auraient pu être plus efficaces, tant dans l'évaporation de l'eau que dans la retenu des nutriments comme le phosphore.

Dans le second volet de cette étude, il a été démontré que la mycorhization pouvait favoriser la croissance de certaines espèces en permettant une plus grande efficacité d'utilisation du phosphore chez la plante. Lors de cette étude, la colonisation par *G. intraradices* a réussi chez tous les plants inoculés, mais l'intensité de la réponse variait selon les espèces. Ainsi, pour *P.* NM5, nous avons noté que la croissance en hauteur était supérieure tout au long de la saison pour les plants mycorhizés, sans pour autant affecter de façon significative la production de biomasse totale. À l'opposé, il a été démontré que la présence d'inoculum avait significativement augmenté la biomasse totale de *S. miyabeana* et *S. viminalis*. Cette augmentation de la productivité se traduisant en une intensification de 33% du contenu total de P dans la partie récoltable de l'arbre, soit la tige, sans que l'inoculum n'ai influencé la concentration du P dans ce compartiment. Lors de cette étude,

aucune différence dans le potentiel de rétention du phosphore n'a pu être observée entre les espèces pour les plants sans inoculation. L'effet de l'inoculum sur ce même potentiel de rétention a toutefois été beaucoup plus marqué pour les saules que pour les peupliers.

En définitive, les résultats de cette étude suggèrent que les saules sont prometteurs pour l'établissement d'un filtre végétal qui contribuerait à réduire les émissions de phosphore en des effluents de pisciculture. En effet, il a été observé que les espèces de saule étudiées répondaient adéquatement aux conditions d'inondation et pourraient accroître leur efficacité à retenir le phosphore en présence de mycorhizes à arbuscules. De futures études en conditions naturelles portant sur la mycorhization de plants soumis à une irrigation intensive seraient nécessaires pour clarifier le potentiel économique de saules et de peupliers pour le traitement des effluents de pisciculture dans une perspective de production de biomasse.

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ANNEXE 1

Résultats des analyses de variance (ANOVA) effectuées sur les données récoltées à la pisciculture de Chartierville (Chapitre 2)

Dependent Variable: conductance stomatale
R-Square: 0.89

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	5	64576	12915	0.64	0.7327
esp	1	930930	930930	33.76	0.0021
bloc*esp	5	137876	27575	0.97	0.5139
irr	1	220559	220559	10.47	0.0231
bloc*irr	5	105316	21063	0.74	0.6259
esp*irr	1	78342	78342	2.75	0.1582
bloc*esp*irr	5	142473	28495	6.77	<.0001
Error	48	202026.667	4208.889		

Tukey Grouping	Mean	N	esp
A	416.61	36	SALIX
B	189.19	36	POP

Tukey Grouping	Mean	N	irr
A	358.25	36	0
B	247.56	36	1

Dependent Variable: hauteur
R-Square: 0.37

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	5	21368	4273.620833	5.26	0.1222
esp	1	24889	24889	51.67	0.0008
bloc*esp	5	2408.604167	481.720833	0.90	0.5446
irr	1	5104.687500	5104.687500	5.90	0.0595
bloc*irr	5	4328.437500	865.687500	1.62	0.3053
esp*irr	1	17.520833	17.520833	0.03	0.8635
bloc*esp*irr	5	2676.104167	535.220833	0.87	0.5000
Error	168	102907.0000	612.5417		

Tukey Grouping	Mean	N	esp
A	124.625	96	POP
B	101.854	96	SALIX

Dependent Variable: diamètre
R-Square: 0.16

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	5	121.568567	24.313713	0.55	0.7393
esp	1	117.437633	117.437633	15.78	0.0106
bloc*esp	5	37.211910	7.442382	0.58	0.7188
irr	1	8.142769	8.142769	0.16	0.7028
bloc*irr	5	249.306538	49.861308	3.87	0.0817
esp*irr	1	77.928033	77.928033	6.06	0.0572
bloc*esp*irr	5	64.340423	12.868085	0.60	0.6966
Error	168	3576.413875	21.288178		

Tukey Grouping	Mean	N	esp
A	19.6926	96	SALIX
B	18.1284	96	POP

Dependent Variable: poids feuilles
R-Square: 0.34

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	5	47116	9423.259375	4.10	0.1312
esp	1	56444	56444	26.50	0.0036
bloc*esp	5	10648	2129.567708	1.62	0.3038
irr	1	35344	35344	23.89	0.0045
bloc*irr	5	7397.635417	1479.527083	1.13	0.4489
esp*irr	1	37716	37716	28.76	0.0030
bloc*esp*irr	5	6556.218750	1311.243750	0.57	0.7253
Error	168	388579.5000	2312.9732		

---------- esp=POP ----------

Tukey Grouping	Mean	N	irr
A	18.454	48	0
B	10.375	48	1

---------- esp=SALIX ----------

Tukey Grouping	Mean	N	irr
A	9.9163	48	0
A	9.7763	48	1

---------- irr=0 ----------

Tukey Grouping	Mean	N	esp
A	18.454	48	POP
B	9.916	48	SALIX

---------- irr=1 ----------

Tukey Grouping	Mean	N	esp
A	10.3754	48	POP
A	9.7763	48	SALIX

Dependent Variable poids bois
R-Square: 0.21

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	5	78397	15679	3.00	0.1149
esp	1	42.187500	42.187500	0.02	0.8990
bloc*esp	5	11825	2364.981250	1.81	0.2652
irr	1	7475.020833	7475.020833	1.80	0.2378
bloc*irr	5	20804	4160.852083	3.19	0.1146
esp*irr	1	330.750000	330.750000	0.25	0.6362
bloc*esp*irr	5	6529.281250	1305.856250	0.47	0.7965
Error	168	464402.2500	2764.2991		

Dependent Variable: poids total
R-Square: 0.21

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	5	77741	15548	3.51	0.0922
esp	1	3852.083333	3852.083333	1.66	0.2538
bloc*esp	5	11593	2318.623958	1.78	0.2711
irr	1	93.520833	93.520833	0.03	0.8750
bloc*irr	5	17059	3411.711458	2.62	0.1571
esp*irr	1	5568.520833	5568.520833	4.28	0.0935
bloc*esp*ir	5	6512.244792	1302.448958	0.47	0.7996
Error	168	467388.5625	2782.0748		

Dependent Variable: specific leaf area
R-Square: 0.94

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	5	1068147	213629	1.86	0.3008
esp	1	2497821	2497821	29.42	0.0029
bloc*esp	5	424459	84892	1.43	0.3534
irr	1	2058.498037	2058.498037	0.02	0.8853
bloc*irr	5	447067	89413	1.50	0.3333
esp*irr	1	60410	60410	1.01	0.3601
Error	5	297798.200	59559.640		

Tukey Grouping	Mean	N	esp
A	1488.0	12	POP
B	842.8	12	SALIX

Dependent Variable: P feuilles (Concentration)
R-Square: 0.96

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	5	0.101288	0.020258	0.48	0.7819
esp	1	0.003504	0.003504	0.14	0.7238
bloc*esp	5	0.125321	0.025064	0.78	0.6048
irr	1	3.337604	3.337604	67.18	0.0004
bloc*irr	5	0.248421	0.049684	1.54	0.3227
esp*irr	1	0.392704	0.392704	12.20	0.0174
Error	5	0.16092083	0.03218417		

esp=POP

Tukey Grouping	Mean	N	irr
A	1.93500	6	0
B	0.93333	6	1

esp=SALIX

Tukey Grouping	Mean	N	irr
A	1.7033	6	0
B	1.2133	6	1

irr=0

Tukey Grouping	Mean	N	esp
A	1.9350	6	POP
A	1.7033	6	SALIX

irr=1

Tukey Grouping	Mean	N	esp
A	1.21333	6	SALIX
B	0.93333	6	POP

Dependent Variable: N feuilles (Concentration)
R-Square: 0.99

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	5	3.024233	0.604847	-1.11	<.0001
esp	1	618.135000	618.135000	3302.18	<.0001
bloc*esp	5	0.935950	0.187190	0.17	0.9637
irr	1	9.375000	9.375000	24.59	0.0043
bloc*irr	5	1.906250	0.381250	0.34	0.8676
esp*irr	1	14.322150	14.322150	12.87	0.0157
Error	5	5.5630000	1.1126000		

esp=POP

Tukey Grouping	Mean	N	irr
A	11.0467	6	0
B	8.2517	6	1

esp=SALIX

Tukey Grouping	Mean	N	irr
A	19.9467	6	1
A	19.6517	6	0

irr=0

Tukey Grouping	Mean	N	esp
A	19.6517	6	SALIX
B	11.0467	6	POP

irr=1

Tukey Grouping	Mean	N	esp
A	19.9467	6	SALIX
B	8.2517	6	POP

Dependent Variable: Ca feuilles (Concentration)
R-Square: 0.99

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	5	7.155821	1.431164	0.60	0.7064
esp	1	49.680037	49.680037	36.53	0.0018
bloc*esp	5	6.800788	1.360158	3.47	0.0994
irr	1	58.250504	58.250504	40.52	0.0014
bloc*irr	5	7.187921	1.437584	3.66	0.0903
esp*irr	1	16.318504	16.318504	41.58	0.0013
Error	5	1.9624208	0.3924842		

esp=POP

Tukey Grouping	Mean	N	irr
A	11.0267	6	0
B	9.5600	6	1

esp=SALIX

Tukey Grouping	Mean	N	irr
A	9.7983	6	0
B	5.0333	6	1

irr=0

Tukey Grouping	Mean	N	esp
A	11.0267	6	POP
B	9.7983	6	SALIX

irr=1

Tukey Grouping	Mean	N	esp
A	9.5600	6	POP
B	5.0333	6	SALIX

Dependent Variable Mg feuilles (Concentration)
R-Square: 0.99

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	5	16.500000	3.300000	0.29	0.8998
esp	1	204.166667	204.166667	19.14	0.0072
bloc*esp	5	53.333333	10.666667	12.31	0.0077
irr	1	864.000000	864.000000	576.00	<.0001
bloc*irr	5	7.500000	1.500000	1.73	0.2809
esp*irr	1	0.166667	0.166667	0.19	0.6793
Error	5	4.333333	0.866667		

Tukey Grouping	Mean	N	esp
A	15.417	12	SALIX
B	9.583	12	POP

Tukey Grouping	Mean	N	irr
A	18.5000	12	0
B	6.5000	12	1

Dependent Variable K feuilles (Concentration)
R-Square: 0.94

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	5	140.000000	28.000000	2.64	0.4244
esp	1	37.500000	37.500000	2.91	0.1489
bloc*esp	5	64.500000	12.900000	0.88	0.5543
irr	1	580.166667	580.166667	46.91	0.0010
bloc*irr	5	61.833333	12.366667	0.84	0.5720
esp*irr	1	192.666667	192.666667	13.14	0.0151
Error	5	73.333333	14.666667		

esp=POP

Tukey Grouping	Mean	N	irr
A	27.540	6	0
B	13.830	6	1

esp=SALIX

Tukey Grouping	Mean	N	irr
A	25.555	6	0
A	22.992	6	1

irr=0

Tukey Grouping	Mean	N	esp
A	27.540	6	POP
A	25.555	6	SALIX

irr=1

Tukey Grouping	Mean	N	esp
A	22.992	6	SALIX
B	13.830	6	POP

Dependent Variable P bois (Concentration)
R-Square: 0.92

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	5	29.500000	5.900000	-0.53	<.0001
esp	1	198.375000	198.375000	27.65	0.0033
bloc*esp	5	35.875000	7.175000	0.38	0.8413
irr	1	782.041667	782.041667	2288.90	<.0001
bloc*irr	5	1.708333	0.341667	0.02	0.9998
esp*irr	1	4.166667	4.166667	0.22	0.6565
Error	5	93.333333	18.666667		

Tukey Grouping	Mean	N	esp
A	15.375	12	POP
B	9.625	12	SALIX

Tukey Grouping	Mean	N	irr
A	18.2083	12	0
B	6.7917	12	1

Dependent Variable: N bois (Concentration)
R-Square: 0.77

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	5	1.382050	0.276410	0.33	0.8647
esp	1	0.048600	0.048600	0.07	0.8074
bloc*esp	5	3.679000	0.735800	1.23	0.4146
irr	1	1.000417	1.000417	1.43	0.2851
bloc*irr	5	3.493483	0.698697	1.16	0.4361
esp*irr	1	0.180267	0.180267	0.30	0.6074
Error	5	3.00323333	0.60064667		

Dependent Variable: Ca bois (Concentration)
R-Square: 0.94

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	5	1.024771	0.204954	0.09	0.9849
esp	1	10.283504	10.283504	71.14	0.0004
bloc*esp	5	0.722771	0.144554	0.14	0.9751
irr	1	48.991837	48.991837	16.03	0.0103
bloc*irr	5	15.277438	3.055488	2.95	0.1299
esp*irr	1	0.242004	0.242004	0.23	0.6491
Error	5	5.17377083	1.03475417		

Tukey Grouping	Mean	N	esp
A	10.6275	12	POP
B	9.3183	12	SALIX

Tukey Grouping	Mean	N	irr
A	11.4017	12	0
B	8.5442	12	1

Dependent Variable: Mg bois (Concentration)
R-Square: 0.99

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	5	0.012121	0.002424	0.20	0.9539
esp	1	0.348004	0.348004	67.13	0.0004
bloc*esp	5	0.025921	0.005184	4.70	0.0574
irr	1	0.148837	0.148837	18.38	0.0078
bloc*irr	5	0.040487	0.008097	7.33	0.0237
esp*irr	1	0.007004	0.007004	6.34	0.0533
Error	5	0.00552083	0.00110417		

Tukey Grouping	Mean	N	esp
A	1.01750	12	SALIX
B	0.77667	12	POP

Tukey Grouping	Mean	N	irr
A	0.97583	12	0
B	0.81833	12	1

Dependent Variable: K bois (Concentration)
R-Square: 0.92

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	5	5.302883	1.060577	0.70	0.6630
esp	1	27.563267	27.563267	15.90	0.0105
bloc*esp	5	8.669683	1.733937	2.31	0.1899
irr	1	0.570417	0.570417	1.06	0.3510
bloc*irr	5	2.698233	0.539647	0.72	0.6372
esp*irr	1	0.582817	0.582817	0.78	0.4187
Error	5	3.75563333	0.75112667		

Tukey Grouping	Mean	N	esp
A	10.3300	12	POP
B	8.1867	12	SALIX

Dependent Variable: P racines (Concentration)
R-Square: 0.97

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	5	0.337521	0.067504	0.97	0.5050
esp	1	1.596504	1.596504	47.88	0.0010
bloc*esp	5	0.166721	0.033344	1.91	0.2470
irr	1	0.598504	0.598504	11.19	0.0204
bloc*irr	5	0.267321	0.053464	3.07	0.1221
esp*irr	1	0.148838	0.148838	8.54	0.0330
Error	5	0.08718750	0.01743750		

---------- esp=POP ----------

Tukey Grouping	Mean	N	irr
A	1.6800	6	0
B	1.2067	6	1

---------- esp=SALIX ----------

Tukey Grouping	Mean	N	irr
A	1.00667	6	0
A	0.84833	6	1

---------- irr=0 ----------

Tukey Grouping	Mean	N	esp
A	1.6800	6	POP
B	1.0067	6	SALIX

---------- irr=1 ----------

Tukey Grouping	Mean	N	esp
A	1.20667	6	POP
B	0.84833	6	SALIX

Dependent Variable: N racines (Concentration)
R-Square: 0.97

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	5	5.750037	1.150007	0.38	0.8466
esp	1	0.002204	0.002204	0.00	0.9654
bloc*esp	5	5.308271	1.061654	5.24	0.0465
irr	1	6.314004	6.314004	2.95	0.1463
bloc*irr	5	10.684371	2.136874	10.56	0.0109
esp*irr	1	0.940104	0.940104	4.64	0.0837
Error	5	1.01207083	0.20241417		

Dependent Variable: Ca racines (Concentration)
R-Square: 0.89

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	5	5.703621	1.140724	0.93	0.6891
esp	1	24.502604	24.502604	10.83	0.0217
bloc*esp	5	11.311221	2.262244	1.07	0.4732
irr	1	38.329537	38.329537	35.03	0.0020
bloc*irr	5	5.471388	1.094278	0.52	0.7579
esp*irr	1	0.643537	0.643537	0.30	0.6057
Error	5	10.61888750	2.12377750		

Tukey Grouping	Mean	N	esp
A	7.7683	12	POP
B	5.7475	12	SALIX

Tukey Grouping	Mean	N	irr
A	8.0217	12	0
B	5.4942	12	1

Dependent Variable: Mg racines (Concentration)
R-Square: 0.86

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	5	0.071471	0.014294	1.27	0.4422
esp	1	0.014504	0.014504	2.32	0.1883
bloc*esp	5	0.031271	0.006254	1.04	0.4848
irr	1	0.000937	0.000937	0.09	0.7823
bloc*irr	5	0.055138	0.011028	1.83	0.2621
esp*irr	1	0.005104	0.005104	0.85	0.3999
Error	5	0.03017083	0.00603417		

Dependent Variable: K racines (Concentration)
R-Square: 0.96

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	5	6.536083	1.307217	0.18	0.9603
esp	1	88.320067	88.320067	22.13	0.0053
bloc*esp	5	19.955483	3.991097	1.92	0.2454
irr	1	93.378150	93.378150	17.14	0.0090
bloc*irr	5	27.243400	5.448680	2.62	0.1567
esp*irr	1	11.343750	11.343750	5.46	0.0666
Error	5	10.3858000	2.0771600		

Tukey Grouping	Mean	N	esp
A	18.4050	12	POP
B	14.5683	12	SALIX

Tukey Grouping	Mean	N	irr
A	18.4592	12	1
B	14.5142	12	0

ANNEXE 2

Résultats des analyses de variance (ANOVA) effectuées sur les données récoltées en milieu semi contrôlé au Jardin Botanique de Montréal (Chapitre 3).

Dependent Variable: hauteur en date du 06/20
R-Square: 0.83

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	3891.131944	1297.043981	1.95	0.4937
esp	2	101030	50515	102.51	<.0001
bloc*esp	6	2956.722222	492.787037	1.15	0.5131
irr	1	68.062500	68.062500	0.20	0.6827
bloc*irr	3	1004.854167	334.951389	0.70	0.6446
esp*irr	2	132.166667	66.083333	0.26	0.7787
bloc*esp*irr	6	1520.333333	253.388889	0.73	0.6414
myc	1	12377	12377	14.89	0.0308
bloc*myc	3	2493.687500	831.229167	1.12	0.4582
esp*myc	2	1724.666667	862.333333	1.66	0.2664
bloc*esp*myc	6	3112.500000	518.750000	1.50	0.3165
irr*myc	1	2.506944	2.506944	0.00	0.9512
bloc*irr*myc	3	1703.743056	567.914352	1.65	0.2760
esp*irr*myc	2	223.388889	111.694444	0.32	0.7354
bloc*esp*irr*myc	6	2070.444444	345.074074	1.17	0.3300
Error	96	28366.6667	295.4861		

Tukey Grouping	Mean	N	esp
A	142.896	48	SM
B	126.729	48	SV
C	80.396	48	POP

Tukey Grouping	Mean	N	myc
A	125.944	72	1
B	107.403	72	0

Dependent Variable: hauteur en date du 07/04
R-Square: 0.77

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	2345.131944	781.710648	1.06	0.6117
esp	2	61940	30970	94.87	<.0001
bloc*esp	6	1958.763889	326.460648	0.82	0.6192
irr	1	88.673611	88.673611	0.25	0.6488
bloc*irr	3	1046.354167	348.784722	0.70	0.6376
esp*irr	2	179.597222	89.798611	0.74	0.5161
bloc*esp*irr	6	728.125000	121.354167	0.52	0.7748
myc	1	9784.506944	9784.506944	9.21	0.0561
bloc*myc	3	3188.854167	1062.951389	1.21	0.4065
esp*myc	2	2843.930556	1421.965278	2.80	0.1381
bloc*esp*myc	6	3042.125000	507.020833	2.19	0.1818
irr*myc	1	68.062500	68.062500	0.11	0.7597
bloc*irr*myc	3	1820.409722	606.803241	2.62	0.1458
esp*irr*myc	2	166.291667	83.145833	0.36	0.7127
bloc*esp*irr*myc	6	1391.319444	231.886574	0.84	0.5452
Error	96	26634.6667	277.4444		

Tukey Grouping	Mean	N	esp
A	163.417	48	SM
A	157.833	48	SV
B	116.896	48	POP

Dependent Variable: hauteur en date du 07/18
R-Square: 0.57

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	173.555556	57.851852	-0.35	<.0001
esp	2	12724	6361.798611	14.59	0.0050
bloc*esp	6	2616.236111	436.039352	0.71	0.6633
irr	1	34.027778	34.027778	0.12	0.7520
bloc*irr	3	851.638889	283.879630	0.51	0.7161
esp*irr	2	188.763889	94.381944	0.93	0.4465
bloc*esp*irr	6	612.069444	102.011574	0.48	0.8036
myc	1	5280.444444	5280.444444	13.23	0.0358
bloc*myc	3	1197.666667	399.222222	0.34	0.7990
esp*myc	2	3999.847222	1999.923611	2.76	0.1410
bloc*esp*myc	6	4341.208333	723.534722	3.40	0.0810
irr*myc	1	51.361111	51.361111	0.08	0.7998
bloc*irr*myc	3	2008.083333	669.361111	3.15	0.1079
esp*irr*myc	2	296.347222	148.173611	0.70	0.5345
bloc*esp*irr*myc	6	1276.375000	212.729167	0.75	0.6076
Error	96	27075.33333	282.03472		

Tukey Grouping	Mean	N	esp
A	188.083	48	SM
A	183.563	48	SV
B	166.271	48	POP

Tukey Grouping	Mean	N	myc
A	185.361	72	1
B	173.250	72	0

Dependent Variable: hauteur en date du 08/01
R-Square: 0.40

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	8757.708333	2919.236111	12.49	0.9719
esp	2	2448.260417	1224.130208	0.43	0.6685
bloc*esp	6	17039	2839.887153	0.56	0.7529
irr	1	42.250000	42.250000	0.07	0.8075
bloc*irr	3	1792.236111	597.412037	1.24	0.6223
esp*irr	2	102.572917	51.286458	0.05	0.9517
bloc*esp*irr	6	6168.982639	1028.163773	1.15	0.4338
myc	1	7482.250000	7482.250000	3.33	0.1654
bloc*myc	3	6733.875000	2244.625000	0.51	0.6954
esp*myc	2	11650	5825.171875	1.17	0.3716
bloc*esp*myc	6	29802	4966.942708	5.57	0.0277
irr*myc	1	10.027778	10.027778	0.03	0.8755
bloc*irr*myc	3	1035.652778	345.217593	0.39	0.7668
esp*irr*myc	2	452.836806	226.418403	0.25	0.7838
bloc*esp*irr*myc	6	5352.357639	892.059606	0.57	0.7521
Error	96	149839.1667	1560.8247		

Dependent Variable: hauteur en date du 08/15
R-Square: 0.56

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	23070	7689.944444	1.58	0.4682
esp	2	27038	13519	3.78	0.0867
bloc*esp	6	21472	3578.651042	0.76	0.6279
irr	1	50.173611	50.173611	0.11	0.7644
bloc*irr	3	1397.743056	465.914352	0.83	0.5805
esp*irr	2	10.690972	5.345486	0.01	0.9914
bloc*esp*irr	6	3724.725694	620.787616	1.42	0.3404
myc	1	2925.006944	2925.006944	0.49	0.5334
bloc*myc	3	17824	5941.210648	1.32	0.3553
esp*myc	2	10225	5112.460069	1.12	0.3854
bloc*esp*myc	6	27326	4554.295718	10.42	0.0059
irr*myc	1	821.777778	821.777778	2.17	0.2371
bloc*irr*myc	3	1135.944444	378.648148	0.87	0.5082
esp*irr*myc	2	618.170139	309.085069	0.71	0.5299
bloc*esp*irr*myc	6	2622.190972	437.031829	0.39	0.8857
Error	96	108407.0000	1129.2396		

Dependent Variable: hauteur en date du 08/27
R-Square: 0.61

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	13608	4535.847222	0.65	0.6634
esp	2	41162	20581	5.32	0.0469
bloc*esp	6	23217	3869.470486	0.73	0.6411
irr	1	36.000000	36.000000	0.03	0.8705
bloc*irr	3	3429.652778	1143.217593	0.66	0.6053
esp*irr	2	153.010417	76.505208	0.07	0.9306
bloc*esp*irr	6	6303.545139	1050.590856	4.29	0.0499
myc	1	390.062500	390.062500	0.05	0.8414
bloc*myc	3	24631	8210.317130	1.58	0.2746
esp*myc	2	7983.010417	3991.505208	0.88	0.4606
bloc*esp*myc	6	27070	4511.655671	18.42	0.0013
irr*myc	1	396.673611	396.673611	0.43	0.5599
bloc*irr*myc	3	2784.729167	928.243056	3.79	0.0775
esp*irr*myc	2	47.649306	23.824653	0.10	0.9087
bloc*esp*irr*myc	6	1469.656250	244.942708	0.24	0.9602
Error	96	95999.5000	999.9948		

Tukey Grouping		Mean	N	esp
	A	95.08	48	POP
B	A	68.01	48	SM
B		54.41	48	SV

Dependent Variable: diamètre en date du 06/20
R-Square: 0.52

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	18168	6055.944444	1.83	0.4582
esp	2	21628	10814	14.91	0.0047
bloc*esp	6	4352.260417	725.376736	0.49	0.7938
irr	1	132.250000	132.250000	2.86	0.1892
bloc*irr	3	138.583333	46.194444	0.03	0.9907
esp*irr	2	1203.510417	601.755208	0.65	0.5556
bloc*esp*irr	6	5561.864583	926.977431	1.67	0.2737
myc	1	45085	45085	8.95	0.0580
bloc*myc	3	15109	5036.351852	3.20	0.1428
esp*myc	2	3949.628472	1974.814236	1.80	0.2445
bloc*esp*myc	6	6590.996528	1098.499421	1.98	0.2127
irr*myc	1	66.694444	66.694444	0.06	0.8156
bloc*irr*myc	3	3090.305556	1030.101852	1.86	0.2373
esp*irr*myc	2	2097.149306	1048.574653	1.89	0.2305
bloc*esp*irr*myc	6	3324.059028	554.009838	0.45	0.8437
Error	96	118310.6667	1232.4028		

Tukey Grouping	Mean	N	esp
A	81.865	48	SM
A	80.448	48	POP
B	55.188	48	SV

Dependent Variable: diamètre en date du 07/04
R-Square: 0.62

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	89.360617	29.786872	16.33	0.5912
esp	2	80.191168	40.095584	38.82	0.0004
bloc*esp	6	6.197188	1.032865	0.19	0.9685
irr	1	0.010678	0.010678	0.00	0.9498
bloc*irr	3	6.863461	2.287820	0.73	0.6114
esp*irr	2	1.176010	0.588005	0.13	0.8785
bloc*esp*irr	6	26.655035	4.442506	2.15	0.1870
myc	1	120.853378	120.853378	25.35	0.0151
bloc*myc	3	14.304239	4.768080	2.62	0.3669
esp*myc	2	22.953768	11.476884	3.64	0.0920
bloc*esp*myc	6	18.893432	3.148905	1.52	0.3110
irr*myc	1	2.678678	2.678678	3.62	0.1534
bloc*irr*myc	3	2.221928	0.740643	0.36	0.7855
esp*irr*myc	2	3.373893	1.686947	0.82	0.4858
bloc*esp*irr*	6	12.400751	2.066792	0.79	0.5804
Error	96	251.3382000	2.6181062		

Tukey Grouping	Mean	N	esp
A	12.2098	48	POP
A	12.1731	48	SM
B	10.6088	48	SV

Tukey Grouping	Mean	N	myc
A	12.5800	72	1
B	10.7478	72	0

Dependent Variable: diamètre en date du 07/18
R-Square: 0.68

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	33.985764	11.328588	10.01	0.8737
esp	2	433.518472	216.759236	185.97	<.0001
bloc*esp	6	6.993194	1.165532	0.14	0.9865
irr	1	0.180625	0.180625	0.10	0.7727
bloc*irr	3	5.425764	1.808588	0.62	0.6673
esp*irr	2	2.348750	1.174375	0.25	0.7843
bloc*esp*ir	6	27.840694	4.640116	2.27	0.1704
myc	1	76.708403	76.708403	10.93	0.0455
bloc*myc	3	21.052431	7.017477	1.66	0.3560
esp*myc	2	17.612639	8.806319	1.49	0.2989
bloc*esp*my	6	35.539028	5.923171	2.90	0.1102
irr*myc	1	2.975625	2.975625	8.83	0.0590
bloc*irr*my	3	1.010764	0.336921	0.17	0.9161
esp*irr*myc	2	6.857917	3.428958	1.68	0.2634
bloc*esp*irr*myc	6	12.244861	2.040810	0.61	0.7213
Error	96	320.893333	3.342639		

Tukey Grouping	Mean	N	esp
A	16.6438	48	POP
B	14.6375	48	SM
C	12.3958	48	SV

Tukey Grouping	Mean	N	myc
A	15.2889	72	1
B	13.8292	72	0

Dependent Variable: diamètre en date du 08/01
R-Square: 0.74

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	17.895950	5.965317	0.95	0.5335
esp	2	703.758126	351.879063	84.15	<.0001
bloc*esp	6	25.089013	4.181502	1.52	0.5368
irr	1	0.161336	0.161336	0.08	0.7983
bloc*irr	3	6.211381	2.070460	-1.72	<.0001
esp*irr	2	2.136126	1.068063	0.71	0.5303
bloc*esp*irr	6	9.072290	1.512048	0.40	0.8530
myc	1	76.125625	76.125625	20.00	0.0208
bloc*myc	3	11.417814	3.805938	1.67	0.5515
esp*myc	2	25.903138	12.951569	2.59	0.1542
bloc*esp*myc	6	29.954357	4.992393	1.33	0.3681
irr*myc	1	0.012844	0.012844	0.01	0.9181
bloc*irr*myc	3	3.089372	1.029791	0.27	0.8417
esp*irr*myc	2	0.394693	0.197347	0.05	0.9491
bloc*esp*irr*myc	6	22.474924	3.745821	1.09	0.3713
Error	96	328.537933	3.422270		

Tukey Grouping	Mean	N	esp
A	18.9519	48	POP
B	16.9892	48	SM
C	13.5998	48	SV

Tukey Grouping	Mean	N	myc
A	17.2407	72	1
B	15.7865	72	0

Dependent Variable: diamètre en date du 08/15
R-Square: 0.72

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	2.376396	0.792132	0.24	0.8749
esp	2	744.952850	372.476425	75.78	<.0001
bloc*esp	6	29.490568	4.915095	42.49	0.9889
irr	1	0.201676	0.201676	0.07	0.8146
bloc*irr	3	9.237418	3.079139	1.51	0.7089
esp*irr	2	8.620102	4.310051	2.69	0.1469
bloc*esp*irr	6	9.629581	1.604930	0.34	0.8954
myc	1	56.111336	56.111336	96.04	0.0023
bloc*myc	3	1.752777	0.584259	0.16	0.9144
esp*myc	2	22.351671	11.175836	3.39	0.1037
bloc*esp*myc	6	19.800936	3.300156	0.69	0.6687
irr*myc	1	0.191479	0.191479	0.04	0.8604
bloc*irr*myc	3	15.676924	5.225641	1.09	0.4221
esp*irr*myc	2	3.855849	1.927925	0.40	0.6854
bloc*esp*irr*myc	6	28.736451	4.789409	1.22	0.3007
Error	96	375.604001	3.912542		

Tukey Grouping	Mean	N	esp
A	19.9946	48	POP
B	18.5189	48	SM
C	14.6042	48	SV

Tukey Grouping	Mean	N	myc
A	18.3301	72	1
B	17.0817	72	0

Dependent Variable: diamètre en date du 08/27
R-Square: 0.69

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	12.477072	4.159024	1.33	0.6744
esp	2	737.080276	368.540138	80.44	<.0001
bloc*esp	6	27.490874	4.581812	0.89	0.5703
irr	1	0.220900	0.220900	0.04	0.8521
bloc*irr	3	16.074050	5.358017	1.82	0.3918
esp*irr	2	1.333804	0.666902	0.25	0.7838
bloc*esp*irr	6	15.771812	2.628635	1.04	0.4797
myc	1	74.390625	74.390625	64.71	0.0040
bloc*myc	3	3.448592	1.149531	0.22	0.8806
esp*myc	2	19.147254	9.573627	1.91	0.2285
bloc*esp*myc	6	30.117596	5.019599	1.99	0.2108
irr*myc	1	1.043803	1.043803	0.37	0.5863
bloc*irr*myc	3	8.478336	2.826112	1.12	0.4115
esp*irr*myc	2	2.653143	1.326572	0.53	0.6154
bloc*esp*irr*myc	6	15.103018	2.517170	0.56	0.7619
Error	96	432.343000	4.503573		

Tukey Grouping	Mean	N	esp
A	20.8208	48	POP
B	19.4244	48	SM
C	15.4781	48	SV

Tukey Grouping	Mean	N	myc
A	19.2932	72	1
B	17.8557	72	0

Dependent Variable: nombre de tiges
R-Square: 0.49

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	4958.402778	1652.800926	-1.64	<.0001
esp	2	35259	17629	8.09	0.0198
bloc*esp	6	13073	2178.760995	0.54	0.7660
irr	1	367.361111	367.361111	0.38	0.5815
bloc*irr	3	2904.208333	968.069444	0.65	0.6299
esp*irr	2	2545.211806	1272.605903	0.72	0.5239
bloc*esp*irr	6	10586	1764.279514	2.49	0.1462
myc	1	1771.006944	1771.006944	5.50	0.1008
bloc*myc	3	966.284722	322.094907	0.12	0.9448
esp*myc	2	1546.732639	773.366319	0.26	0.7800
bloc*esp*myc	6	17908	2984.725116	4.21	0.0520
irr*myc	1	370.562500	370.562500	0.85	0.4242
bloc*irr*myc	3	1305.618056	435.206019	0.61	0.6310
esp*irr*myc	2	455.760417	227.880208	0.32	0.7371
bloc*esp*irr*myc	6	4258.767361	709.794560	0.65	0.6876
Error	96	104350.3333	1086.9826		

Tukey Grouping		Mean	N	esp
	A	89.740	48	SV
B	A	75.896	48	POP
B		51.865	48	SM

Dependent Variable: poids feuilles
R-Square: 0.77

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	2288.665847	762.888616	1.82	0.2726
esp	2	16162	8081.059672	18.04	0.0029
bloc*esp	6	2687.507385	447.917897	5.10	0.1500
irr	1	11.908251	11.908251	0.21	0.6801
bloc*irr	3	172.666719	57.555573	0.91	0.6094
esp*irr	2	82.602901	41.301451	0.45	0.6550
bloc*esp*irr	6	545.411204	90.901867	1.14	0.4377
myc	1	304.182667	304.182667	5.78	0.0955
bloc*myc	3	157.903858	52.634619	1.08	0.6194
esp*myc	2	145.891985	72.945992	0.95	0.4367
bloc*esp*myc	6	458.703265	76.450544	0.96	0.5186
irr*myc	1	35.710584	35.710584	0.69	0.4677
bloc*irr*myc	3	155.766452	51.922151	0.65	0.6098
esp*irr*myc	2	241.722226	120.861113	1.52	0.2925
bloc*esp*irr*myc	6	477.291579	79.548597	1.09	0.3757
Error	96	7024.81713	73.17518		

Tukey Grouping	Mean	N	esp
A	62.676	48	POP
A	62.478	48	SM
B	40.104	48	SV

Dependent Variable: poids bois
R-Square: 0.67

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	9030.007728	3010.002576	2.07	0.2861
esp	2	45854	22927	23.07	0.0015
bloc*esp	6	5964.637822	994.106304	3.66	0.2912
irr	1	829.796570	829.796570	1.38	0.3249
bloc*irr	3	1804.514671	601.504890	0.92	0.5500
esp*irr	2	1169.666271	584.833135	1.98	0.2189
bloc*esp*irr	6	1774.250642	295.708440	0.88	0.5595
myc	1	18825	18825	22.77	0.0175
bloc*myc	3	2480.153670	826.717890	1.23	0.4611
esp*myc	2	6551.547004	3275.773502	10.50	0.0109
bloc*esp*myc	6	1871.761994	311.960332	0.93	0.5346
irr*myc	1	24.998599	24.998599	0.04	0.8615
bloc*irr*myc	3	2080.450122	693.483374	2.06	0.2064
esp*irr*myc	2	933.151267	466.575634	1.39	0.3194
bloc*esp*irr*	6	2015.561299	335.926883	0.64	0.6960
Error	95	49671.8040	522.8611		

---------- esp=POP ----------

Tukey Grouping	Mean	N	myc
A	153.059	24	1
A	141.050	24	0

---------- esp=SM ----------

Tukey Grouping	Mean	N	myc
A	200.123	24	1
B	157.105	23	0

---------- esp=SV ----------

Tukey Grouping	Mean	N	myc
A	196.279	24	1
B	181.524	24	0

---------- myc=0 ----------

Tukey Grouping	Mean	N	esp
A	181.524	24	SV
B	157.105	23	SM
B	141.050	24	POP

---------- myc=1 ----------

Tukey Grouping	Mean	N	esp
A	200.123	24	SM
A	196.279	24	SV
B	153.059	24	POP

Dependent Variable: poids total
R-Square: 0.61

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	10476	3491.947097	1.83	0.4027
esp	2	56843	28421	11.44	0.0090
bloc*esp	6	14907	2484.494645	1.66	0.2682
irr	1	895.974733	895.974733	0.90	0.4124
bloc*irr	3	2981.579246	993.859749	0.58	0.6534
esp*irr	2	2017.620605	1008.810303	0.84	0.4772
bloc*esp*irr	6	7215.694993	1202.615832	3.10	0.0974
myc	1	24019	24019	28.65	0.0127
bloc*myc	3	2514.851348	838.283783	0.69	0.6034
esp*myc	2	7516.944553	3758.472277	5.50	0.0439
bloc*esp*myc	6	4101.309222	683.551537	1.76	0.2546
irr*myc	1	220.213058	220.213058	0.24	0.6567
bloc*irr*myc	3	2734.195200	911.398400	2.35	0.1721
esp*irr*myc	2	2238.004196	1119.002098	2.88	0.1327
bloc*esp*irr*myc	6	2330.485015	388.414169	0.41	0.8692
Error	95	89473.5281	941.8266		

---------- esp=POP ----------

Tukey Grouping	Mean	N	myc
A	237.036	24	1
A	222.806	24	0

---------- esp=SM ----------

Tukey Grouping	Mean	N	myc
A	301.10	24	1
B	253.81	23	0

---------- esp=SV ----------

Tukey Grouping	Mean	N	myc
A	271.118	24	1
B	253.998	24	0

---------- myc=0 ----------

Tukey Grouping	Mean	N	esp
A	253.998	24	SV
A	253.809	23	SM
B	222.806	24	POP

---------- myc=1 ----------

Tukey Grouping	Mean	N	esp
A	301.10	24	SM
B A	271.12	24	SV
B	237.04	24	POP

Dependent Variable: specific leaf area
R-Square: 0.95

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	23.012675	7.670892	13.50	0.2744
esp	2	9.341554	4.670777	10.38	0.0113
bloc*esp	6	2.699812	0.449969	0.71	0.6704
irr	1	0.216008	0.216008	0.44	0.5528
bloc*irr	3	1.458942	0.486314	0.68	0.6192
esp*irr	2	1.566254	0.783127	1.08	0.3981
bloc*esp*irr	6	4.358546	0.726424	1.79	0.2479
myc	1	0.122008	0.122008	0.19	0.6959
bloc*myc	3	1.975442	0.658481	2.19	0.4624
esp*myc	2	1.037554	0.518777	1.66	0.2668
bloc*esp*myc	6	1.875046	0.312508	0.77	0.6198
irr*myc	1	0.407008	0.407008	1.04	0.3837
bloc*irr*myc	3	1.178375	0.392792	0.97	0.4664
esp*irr*myc	2	0.044954	0.022477	0.06	0.9465
Error	6	2.43161250	0.40526875		

Tukey Grouping		Mean	N	esp
	A	8.7300	16	SM
B	A	8.2819	16	SV
B		7.6544	16	POP

Dependent Variable: P feuilles (Concentration)
R-Square: 0.98

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	439.125000	146.375000	1.07	0.4972
esp	2	3804.875000	902.437500	30.51	0.0007
bloc*esp	6	374.125000	62.354167	5.16	0.4642
irr	1	3234.083333	3234.083333	118.50	0.0017
bloc*irr	3	81.875000	27.291667	0.44	0.7449
esp*irr	2	130.791667	65.395833	2.75	0.1423
bloc*esp*irr	6	142.875000	23.812500	0.88	0.5602
myc	1	3.000000	3.000000	0.02	0.8863
bloc*myc	3	372.375000	124.125000	2.33	0.3316
esp*myc	2	130.875000	65.437500	4.26	0.0705
bloc*esp*myc	6	92.125000	15.354167	0.57	0.7463
irr*myc	1	3.000000	3.000000	0.05	0.8438
bloc*irr*myc	3	195.208333	65.069444	2.40	0.1662
esp*irr*myc	2	42.125000	21.062500	0.78	0.5009
Error	6	162.541667	27.090278		

Tukey Grouping	Mean	N	esp
A	34.063	16	POP
A	26.813	16	SV
B	12.625	16	SM

Tukey Grouping	Mean	N	irr
A	32.708	24	1
B	16.292	24	0

Dependent Variable: N feuilles (Concentration)
R-Square: 0.98

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	34.305908	11.435303	5.50	0.2300
esp	2	138.549117	69.274558	40.80	0.0003
bloc*esp	6	10.187117	1.697853	1.54	0.3829
irr	1	2.025408	2.025408	12.76	0.0375
bloc*irr	3	0.476208	0.158736	0.11	0.9472
esp*irr	2	3.899817	1.949908	1.77	0.2484
bloc*esp*irr	6	6.601317	1.100219	1.48	0.3240
myc	1	6.690133	6.690133	2.80	0.1927
bloc*myc	3	7.160550	2.386850	2.25	0.3212
esp*myc	2	5.652817	2.826408	3.77	0.0871
bloc*esp*myc	6	4.499650	0.749942	1.01	0.4969
irr*myc	1	0.374533	0.374533	0.35	0.5936
bloc*irr*myc	3	3.172050	1.057350	1.42	0.3264
esp*irr*myc	2	1.552317	0.776158	1.04	0.4089
Error	6	4.4704500	0.7450750		

Tukey Grouping	Mean	N	esp
A	17.4325	16	SV
B	14.3838	16	POP
B	13.4550	16	SM

Tukey Grouping	Mean	N	irr
A	15.2958	24	0
B	14.8850	24	1

Dependent Variable: Ca feuilles (Concentration)
R-Square: 0.97

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	187.291667	62.430556	1.01	0.5244
esp	2	7974.125000	3987.062500	326.77	<.0001
bloc*esp	6	73.208333	12.201389	0.65	0.7729
irr	1	0.520833	0.520833	0.01	0.9260
bloc*irr	3	153.687500	51.229167	-12.05	<.0001
esp*irr	2	1.166667	0.583333	0.02	0.9815
bloc*esp*irr	6	186.750000	31.125000	0.72	0.6476
myc	1	0.520833	0.520833	0.02	0.8942
bloc*myc	3	74.687500	24.895833	-5.41	<.0001
esp*myc	2	11.791667	5.895833	0.19	0.8305
bloc*esp*myc	6	184.625000	30.770833	0.72	0.6526
irr*myc	1	30.083333	30.083333	3.95	0.1412
bloc*irr*myc	3	22.875000	7.625000	0.18	0.9080
esp*irr*myc	2	50.666667	25.333333	0.59	0.5840
Error	6	258.000000	43.000000		

Tukey Grouping	Mean	N	esp
A	40.500	16	SM
B	24.063	16	POP
C	8.938	16	SV

Dependent Variable: Mg feuilles (Concentration)
R-Square: 0.97

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	0.720975	0.240325	3.92	0.3053
esp	2	9.236254	4.618127	230.21	<.0001
bloc*esp	6	0.120362	0.020060	0.81	0.7610
irr	1	0.002408	0.002408	2.08	0.2450
bloc*irr	3	0.003475	0.001158	-0.04	<.0001
esp*irr	2	0.015804	0.007902	0.24	0.7919
bloc*esp*ir	6	0.195412	0.032569	0.51	0.7866
myc	1	0.020833	0.020833	0.30	0.6199
bloc*myc	3	0.205683	0.068561	-16.98	<.0001
esp*myc	2	0.003654	0.001827	0.03	0.9684
bloc*esp*myc	6	0.339429	0.056572	0.88	0.5608
irr*myc	1	0.043200	0.043200	11.29	0.0438
bloc*irr*myc	3	0.011483	0.003828	0.06	0.9793
esp*irr*myc	2	0.037588	0.018794	0.29	0.7570
Error	6	0.38662917	0.06443819		

Tukey Grouping	Mean	N	esp
A	3.01250	16	SV
B	2.73813	16	POP
C	1.97563	16	SM

Dependent Variable: K feuilles (Concentration)
R-Square: 0.99

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	243.577717	81.192572	5.69	0.3134
esp	2	841.606504	420.803252	24.77	0.0013
bloc*esp	6	101.945246	16.990874	0.91	0.5333
irr	1	33.233408	33.233408	2.70	0.1988
bloc*irr	3	36.911342	12.303781	0.89	0.5055
esp*irr	2	16.740804	8.370402	1.03	0.4113
bloc*esp*irr	6	48.577346	8.096224	2.68	0.1278
myc	1	2.159008	2.159008	0.17	0.7046
bloc*myc	3	37.221342	12.407114	0.64	0.6137
esp*myc	2	4.705254	2.352627	0.17	0.8455
bloc*esp*myc	6	81.802096	13.633683	4.51	0.0446
irr*myc	1	0.488033	0.488033	0.06	0.8281
bloc*irr*myc	3	26.133150	8.711050	2.88	0.1249
esp*irr*myc	2	6.745754	3.372877	1.12	0.3871
Error	6	18.126062	3.021010		

Tukey Grouping	Mean	N	esp
A	53.991	16	POP
A	53.834	16	SV
B	45.031	16	SM

Dependent Variable: P bois (Concentration)
R-Square: 0.86

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	0.050223	0.016741	0.35	0.8091
esp	2	0.246779	0.123390	2.94	0.1288
bloc*esp	6	0.251721	0.041953	2.32	0.5904
irr	1	0.103602	0.103602	2.65	0.2023
bloc*irr	3	0.117473	0.039158	1.66	0.6029
esp*irr	2	0.054629	0.027315	1.09	0.3932
bloc*esp*irr	6	0.149671	0.024945	0.58	0.7369
myc	1	0.065269	0.065269	2.51	0.2115
bloc*myc	3	0.078106	0.026035	0.75	0.6601
esp*myc	2	0.064912	0.032456	0.90	0.4553
bloc*esp*myc	6	0.216488	0.036081	0.84	0.5807
irr*myc	1	0.007252	0.007252	0.17	0.7040
bloc*irr*myc	3	0.124490	0.041497	0.97	0.4673
esp*irr*myc	2	0.034029	0.017015	0.40	0.6891
Error	6	0.25750417	0.04291736		

Dependent Variable: N bois (Concentration)
R-Square: 0.96

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	7.480973	2.493658	-54.40	<.0001
esp	2	11.414529	5.707265	19.06	0.0025
bloc*esp	6	1.796471	0.299412	3.77	0.5361
irr	1	0.752502	0.752502	13.15	0.0361
bloc*irr	3	0.171623	0.057208	0.16	0.9141
esp*irr	2	0.414429	0.207215	1.14	0.3807
bloc*esp*irr	6	1.091171	0.181862	0.96	0.5178
myc	1	0.001752	0.001752	0.05	0.8413
bloc*myc	3	0.110473	0.036824	0.14	0.9237
esp*myc	2	0.210554	0.105277	1.22	0.3600
bloc*esp*myc	6	0.519046	0.086508	0.46	0.8178
irr*myc	1	0.085852	0.085852	0.24	0.6587
bloc*irr*myc	3	1.079473	0.359824	1.90	0.2300
esp*irr*myc	2	0.098554	0.049277	0.26	0.7787
Error	6	1.13344583	0.18890764		

Tukey Grouping	Mean	N	esp
A	3.7725	16	POP
B	2.9963	16	SV
B	2.5981	16	SM

Tukey Grouping	Mean	N	irr
A	3.24750	24	1
B	2.99708	24	0

Dependent Variable: Ca bois (Concentration)
R-Square: 0.90

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	16.009690	5.336563	-3.53	<.0001
esp	2	68.274429	34.137215	17.70	0.0030
bloc*esp	6	11.572604	1.928767	2.00	0.6441
irr	1	0.015052	0.015052	0.05	0.8328
bloc*irr	3	0.852256	0.284085	0.14	0.9237
esp*irr	2	0.477529	0.238765	0.18	0.8416
bloc*esp*irr	6	8.072338	1.345390	0.53	0.7707
myc	1	1.790269	1.790269	3.91	0.1423
bloc*myc	3	1.372273	0.457424	0.16	0.9129
esp*myc	2	3.558537	1.779269	0.82	0.4831
bloc*esp*myc	6	12.964296	2.160716	0.85	0.5754
irr*myc	1	0.030502	0.030502	0.01	0.9286
bloc*irr*myc	3	9.651606	3.217202	1.27	0.3672
esp*irr*myc	2	0.803454	0.401727	0.16	0.8572
Error	6	15.2436125	2.5406021		

Tukey Grouping		Mean	N	esp
	A	8.3725	16	SM
B	A	6.9331	16	POP
B		5.4513	16	SV

Dependent Variable: Mg bois (Concentration)
R-Square: 0.94

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	0.047740	0.015913	-0.84	<.0001
esp	2	0.478887	0.239444	14.85	0.0047
bloc*esp	6	0.096729	0.016122	1.59	0.4603
irr	1	0.013002	0.013002	1.08	0.3749
bloc*irr	3	0.036090	0.012030	0.28	0.8400
esp*irr	2	0.031129	0.015565	1.06	0.4029
bloc*esp*irr	6	0.087954	0.014659	1.38	0.3529
myc	1	0.000469	0.000469	0.19	0.6896
bloc*myc	3	0.007256	0.002419	0.07	0.9715
esp*myc	2	0.035588	0.017794	2.91	0.1307
bloc*esp*myc	6	0.036662	0.006110	0.58	0.7408
irr*myc	1	0.001519	0.001519	0.04	0.8568
bloc*irr*myc	3	0.118106	0.039369	3.71	0.0808
esp*irr*myc	2	0.017713	0.008856	0.83	0.4792
Error	6	0.06373750	0.01062292		

Tukey Grouping	Mean	N	esp
A	0.68750	16	SV
A	0.59438	16	POP
B	0.44500	16	SM

Dependent Variable: K bois (Concentration)
R-Square: 0.97

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	18.059523	6.019841	1.37	0.5924
esp	2	255.222317	127.611158	19.98	0.0022
bloc*esp	6	38.323483	6.387247	0.93	0.5362
irr	1	13.899769	13.899769	3.97	0.1402
bloc*irr	3	10.492240	3.497413	0.54	0.6767
esp*irr	2	5.274050	2.637025	0.43	0.6701
bloc*esp*irr	6	36.944817	6.157469	2.75	0.1215
myc	1	0.899269	0.899269	0.23	0.6636
bloc*myc	3	11.672873	3.890958	1.21	0.4641
esp*myc	2	2.264600	1.132300	0.39	0.6937
bloc*esp*myc	6	17.465133	2.910856	1.30	0.3784
irr*myc	1	4.594219	4.594219	1.81	0.2711
bloc*irr*myc	3	7.611423	2.537141	1.13	0.4075
esp*irr*myc	2	1.416200	0.708100	0.32	0.7400
Error	6	13.4147333	2.2357889		

Tukey Grouping	Mean	N	esp
A	14.9344	16	POP
B	10.3631	16	SV
B	9.7756	16	SM

Dependent Variable: P racines (Concentration)
R-Square: 0.98

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	0.319642	0.106547	-1.65	<.0001
esp	2	6.875679	3.437840	40.50	0.0003
bloc*esp	6	0.509321	0.084887	0.61	0.7209
irr	1	1.280533	1.280533	17.95	0.0241
bloc*irr	3	0.214017	0.071339	0.35	0.7954
esp*irr	2	0.009254	0.004627	0.06	0.9425
bloc*esp*irr	6	0.464046	0.077341	1.69	0.2707
myc	1	0.012033	0.012033	0.13	0.7440
bloc*myc	3	0.281650	0.093883	0.40	0.7630
esp*myc	2	0.036954	0.018477	0.17	0.8474
bloc*esp*myc	6	0.651413	0.108569	2.37	0.1591
irr*myc	1	0.054675	0.054675	0.31	0.6149
bloc*irr*myc	3	0.523975	0.174658	3.81	0.0768
esp*irr*myc	2	0.277213	0.138606	3.02	0.1236
Error	6	0.27518750	0.04586458		

Tukey Grouping	Mean	N	esp
A	2.4413	16	SV
A	2.1656	16	SM
B	1.5369	16	POP

Tukey Grouping	Mean	N	irr
A	2.21125	24	1
B	1.88458	24	0

Dependent Variable: N racines (Concentration)
R-Square: 0.92

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	670.625000	223.541667	-1.02	<.0001
esp	2	94.718750	47.359375	0.14	0.8760
bloc*esp	6	2099.531250	349.921875	0.71	0.6589
irr	1	7.520833	7.520833	0.07	0.8069
bloc*irr	3	316.854167	105.618056	0.47	0.7310
esp*irr	2	208.635417	104.317708	0.98	0.4269
bloc*esp*irr	6	635.864583	105.977431	0.89	0.5531
myc	1	67.687500	67.687500	1.21	0.3521
bloc*myc	3	168.187500	56.062500	0.09	0.9631
esp*myc	2	209.656250	104.828125	0.21	0.8185
bloc*esp*myc	6	3037.593750	506.265625	4.26	0.0505
irr*myc	1	8.333333	8.333333	0.04	0.8632
bloc*irr*myc	3	710.625000	236.875000	1.99	0.2163
esp*irr*myc	2	261.697917	130.848958	1.10	0.3912
Error	6	712.468750	118.744792		

Dependent Variable: Ca racines (Concentration)
R-Square: 0.99

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	6.462783	2.154261	1.29	0.6386
esp	2	121.734600	60.867300	24.12	0.0014
bloc*esp	6	15.141117	2.523519	1.77	0.2449
irr	1	8.840833	8.840833	4.10	0.1359
bloc*irr	3	6.462283	2.154094	0.83	0.5499
esp*irr	2	0.743317	0.371658	0.55	0.6048
bloc*esp*irr	6	4.073567	0.678928	1.78	0.2512
myc	1	0.016875	0.016875	0.02	0.8887
bloc*myc	3	2.187775	0.729258	0.24	0.8663
esp*myc	2	3.834200	1.917100	1.69	0.2612
bloc*esp*myc	6	6.794050	1.132342	2.96	0.1060
irr*myc	1	1.786408	1.786408	0.77	0.4442
bloc*irr*myc	3	6.938342	2.312781	6.05	0.0302
esp*irr*myc	2	1.309717	0.654858	1.71	0.2579
Error	6	2.2934333	0.3822389		

Tukey Grouping	Mean	N	esp
A	11.8625	16	POP
B	9.6950	16	SV
C	7.9700	16	SM

Dependent Variable: Mg racines (Concentration)
R-Square: 0.95

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	0.136106	0.045369	-3.20	<.0001
esp	2	0.377154	0.188577	3.44	0.1012
bloc*esp	6	0.329063	0.054844	0.60	0.7277
irr	1	0.000018750	0.000018750	0.00	0.9844
bloc*irr	3	0.124123	0.041374	0.90	0.5268
esp*irr	2	0.132088	0.066044	1.87	0.2339
bloc*esp*irr	6	0.211996	0.035333	1.63	0.2847
myc	1	0.085852	0.085852	6.10	0.0901
bloc*myc	3	0.042223	0.014074	0.16	0.9205
esp*myc	2	0.146154	0.073077	0.93	0.4444
bloc*esp*myc	6	0.470896	0.078483	3.61	0.0716
irr*myc	1	0.040252	0.040252	1.24	0.3463
bloc*irr*myc	3	0.097190	0.032397	1.49	0.3091
esp*irr*myc	2	0.250454	0.125227	5.77	0.0401
Error	6	0.13032917	0.02172153		

---------- esp=POP irr=0 ----------

Tukey Grouping	Mean	N	myc
A	1.06250	4	1
A	0.88750	4	0

---------- esp=POP irr=1 ----------

Tukey Grouping	Mean	N	myc
A	0.89750	4	0
A	0.78750	4	1

---------- esp=SM irr=0 ----------

Tukey Grouping	Mean	N	myc
A	1.2325	4	0
B	0.8075	4	1

---------- esp=SM irr=1 ----------

Tukey Grouping	Mean	N	myc
A	1.0525	4	0
A	1.0125	4	1

---------- esp=SV irr=0 ----------

Tukey Grouping	Mean	N	myc
A	1.1525	4	0
A	0.9750	4	1

---------- esp=SV irr=1 ----------

Tukey Grouping	Mean	N	myc
A	1.2225	4	1
A	1.1525	4	0

---------- esp=POP myc=0 ----------

Tukey Grouping	Mean	N	irr
A	0.89750	4	1
A	0.88750	4	0

---------- esp=POP myc=1 ----------

Tukey Grouping	Mean	N	irr
A	1.06250	4	0
B	0.78750	4	1

---------- esp=SM myc=0 ----------

Tukey Grouping	Mean	N	irr
A	1.2325	4	0
A	1.0525	4	1

---------- esp=SM myc=1 ----------

Tukey Grouping	Mean	N	irr
A	1.01250	4	1
B	0.80750	4	0

---------- esp=SV myc=0 ----------

Tukey Grouping	Mean	N	irr
A	1.1525	4	0
A	1.1525	4	1

---------- esp=SV myc=1 ----------

Tukey Grouping	Mean	N	irr
A	1.2225	4	1
A	0.9750	4	0

---------- irr=0 myc=0 ----------

Tukey Grouping	Mean	N	esp
A	1.2325	4	SM
A	1.1525	4	SV
A	0.8875	4	POP

---------- irr=0 myc=1 ----------

Tukey Grouping	Mean	N	esp
A	1.0625	4	POP
A	0.9750	4	SV
A	0.8075	4	SM

---------- irr=1 myc=0 ----------

Tukey Grouping	Mean	N	esp
A	1.1525	4	SV
A	1.0525	4	SM
A	0.8975	4	POP

---------- irr=1 myc=1 ----------

Tukey Grouping		Mean	N	esp
	A	1.2225	4	SV
B	A	1.0125	4	SM
B		0.7875	4	POP

Dependent Variable: K racines (Concentration)
R-Square: 0.88

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	8.785733	2.928578	0.67	0.8499
esp	2	17.217262	8.608631	1.63	0.2725
bloc*esp	6	31.739904	5.289984	0.53	0.7695
irr	1	23.576033	23.576033	15.17	0.0300
bloc*irr	3	4.661100	1.553700	0.43	0.7959
esp*irr	2	0.132929	0.066465	0.03	0.9734
bloc*esp*irr	6	14.712138	2.452023	0.45	0.8244
myc	1	0.009075	0.009075	0.00	0.9815
bloc*myc	3	42.780892	14.260297	1.00	0.4755
esp*myc	2	1.264363	0.632181	0.05	0.9532
bloc*esp*myc	6	78.490171	13.081695	2.39	0.1566
irr*myc	1	2.970075	2.970075	0.45	0.5518
bloc*irr*myc	3	19.957558	6.652519	1.21	0.3824
esp*irr*myc	2	2.853012	1.426506	0.26	0.7790
Error	6	32.8571542	5.4761924		

Tukey Grouping	Mean	N	irr
A	19.1208	24	0
B	17.7192	24	1

Dependent Variable: taux de mycorhization (en %)
R-Square: 0.99

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	2.125000	0.708333	0.14	0.9310
esp	2	890.333333	445.166667	140.58	<.0001
bloc*esp	6	19.000000	3.166667	2.11	0.1926
irr	1	9.375000	9.375000	2.78	0.1942
bloc*irr	3	10.125000	3.375000	2.25	0.1829
esp*irr	2	507.000000	253.500000	169.00	<.0001
Error	6	9.000000	1.500000		

---------- esp=POP ----------

Tukey Grouping	Mean	N	irr
A	29.000	4	0
B	14.750	4	1

---------- esp=SM ----------

Tukey Grouping	Mean	N	irr
A	12.250	4	1
B	7.000	4	0

---------- esp=SV ----------

Tukey Grouping	Mean	N	irr
A	11.0000	4	1
B	5.7500	4	0

---------- irr=0 ----------

Tukey Grouping	Mean	N	esp
A	29.000	4	POP
B	7.000	4	SM
B	5.750	4	SV

---------- irr=1 ----------

Tukey Grouping	Mean	N	esp
A	14.7500	4	POP
B	12.2500	4	SM
B	11.0000	4	SV

Dependent Variable: ratio poids racines/total (en %)
R-Square: 0.95

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	16.068284	5.356095	0.43	0.8861
esp	2	159.981407	79.990704	4.42	0.0661
bloc*esp	6	108.620063	18.103344	0.37	0.8783
irr	1	9.408916	9.408916	1.26	0.3440
bloc*irr	3	22.475026	7.491675	0.23	0.8738
esp*irr	2	42.344046	21.172023	0.71	0.5287
bloc*esp*irr	6	178.878927	29.813154	3.28	0.0868
myc	1	82.263818	82.263818	1.72	0.2815
bloc*myc	3	143.831702	47.943901	1.54	0.3139
esp*myc	2	67.116105	33.558052	1.20	0.3652
bloc*esp*myc	6	168.225209	28.037535	3.09	0.0979
irr*myc	1	0.113474	0.113474	0.01	0.9293
bloc*irr*myc	3	36.642188	12.214063	1.35	0.3454
esp*irr*myc	2	10.011153	5.005576	0.55	0.6028

Dependent Variable: P feuilles (Contenu)
R-Square: 0.98

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	284.541667	94.847222	1.11	0.5467
esp	2	5943.875000	2971.937500	76.50	<.0001
bloc*esp	6	233.083333	38.847222	0.42	0.8453
irr	1	1210.020833	1210.020833	15.37	0.0295
bloc*irr	3	236.187500	78.729167	5.16	0.3880
esp*irr	2	0.166667	0.083333	0.00	0.9977
bloc*esp*irr	6	213.875000	35.645833	1.43	0.3364
myc	1	1.687500	1.687500	0.03	0.8833
bloc*myc	3	198.604167	66.201389	1.06	0.4777
esp*myc	2	54.125000	27.062500	0.33	0.7330
bloc*esp*myc	6	496.083333	82.680556	3.33	0.0847
irr*myc	1	75.000000	75.000000	16.72	0.0264
bloc*irr*myc	3	13.458333	4.486111	0.18	0.9059
esp*irr*myc	2	99.125000	49.562500	1.99	0.2168

Tukey Grouping	Mean	N	esp
A	38.313	16	POP
B	24.125	16	SM
C	11.063	16	SV

---------- myc=0 ----------

Tukey Grouping	Mean	N	irr
A	214.00	12	1
A	170.58	12	0

---------- myc=1 ----------

Tukey Grouping	Mean	N	irr
A	230.33	12	1
B	164.67	12	0

Dependent Variable: P bois (Contenu)
R-Square: 0.95

Source	DF	Type III SS	Mean Square	F Value	Pr > F
bloc	3	9679.973380	3226.657793	2.07	0.4952
esp	2	25295	12648	5.30	0.0451
bloc*esp	6	14699	2449.771412	1.84	0.4077
irr	1	6142.540179	6142.540179	5.20	0.1014
bloc*irr	3	3558.278935	1186.092978	0.53	0.6868
esp*irr	2	420.031250	210.015625	0.10	0.9042
bloc*esp*irr	6	12593	2098.885995	2.00	0.2321
myc	1	6375.111607	6375.111607	12.26	0.0313
bloc*myc	3	1500.760417	500.253472	1.08	0.7460
esp*myc	2	5632.062500	2816.031250	8.95	0.0090
bloc*esp*myc	6	1677.989583	279.664931	0.27	0.9309
irr*myc	1	42.004464	42.004464	0.03	0.8632
bloc*irr*myc	3	3634.510417	1211.503472	1.15	0.4133
esp*irr*myc	2	581.031250	290.515625	0.28	0.7692

---------- esp=POP ----------

Tukey Grouping	Mean	N	myc
A	153.625	8	1
A	143.875	8	0

---------- esp=SM ----------

Tukey Grouping	Mean	N	myc
A	230.88	8	1
B	174.25	8	0

---------- esp=SV ----------

Tukey Grouping	Mean	N	myc
A	196.125	8	1
A	178.429	7	0

---------- myc=0 ----------

Tukey Grouping	Mean	N	esp
A	178.43	7	SV
A	174.25	8	SM
A	143.88	8	POP

---------- myc=1 ----------

Tukey Grouping	Mean	N	esp
A	230.88	8	SM
A	196.13	8	SV
B	153.63	8	POP