# Optimisation de la production d'amandes par la gestion de l'irrigation en temps réel

**Mémoire**

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# Résumé

La présente étude était divisée en deux volets. Le premier volet consistait à évaluer l'effet sur les rendements d'amandes, de la consommation en eau et de la réponse de ces arbres à quatre traitements de déclenchement d'irrigation. Trois de ces traitements reposaient sur le déclenchement de l'irrigation selon des seuils de potentiel matriciel de l'eau du sol (SWTT) (humide (-35 kPa), modéré (-45 kPa), sec (-55 kPa)) tandis que le quatrième était régi selon les techniques actuelles du producteur basées principalement sur le calcul de l'évapotranspiration de la culture (ETc). L'expérimentation a été menée durant la période de mai à août de 2012 à 2015 sur 16 rangées de 22 arbres d'amandiers de la variété Nonpareil. Les rangées étaient subdivisées en 4 blocs de 4 traitements. Pour chaque traitement du bloc 2, trois tensiomètres étaient installés à trois profondeurs différentes soient à 25, 50 et 50 cm. L'irrigation de chacun des traitements était contrôlée à distance pour ne jamais dépasser le seuil de tension prescrit. Les résultats montrent qu'une gestion d'irrigation basée sur un SWTT de -45 kPa durant la période du début mai à la récolte permettrait d'économiser 20% d'eau d'irrigation sans diminuer les rendements. Ces résultats indiquent aussi qu'une gestion humide (-35 kPa) influencerait tout autant les rendements qu'une gestion sèche (-55 kPa).

Le second volet était d'ajuster le seuil optimal de -45 kPa établit au premier volet en fonction de la variabilité spatio-temporelle et des conséquences économiques liées à la mesure de la tension. L'expérimentation de ce volet a été effectuée de la fin juin à la fin juillet 2015 dans un champ de 30 ha. Le dispositif était constitué de 27 stations de 2 tensiomètres (25 et 50 cm) positionnées de manière uniforme dans le champ et les rangées d'arbres de la variété Nonpareil. Les analyses et les simulations indiquent qu'il serait économiquement avantageux d'utiliser 5 stations par champ de 30 ha et d'irriguer lorsque la moyenne des tensions à 25 et 50 cm des 5 stations atteint -45 kPa.

# Abstract

The present study was divided in two parts. The first part consisted in evaluating the effect on almond yield, water consumption and plant response of four different triggering irrigation treatments. Three of these treatments were based on soil water tension thresholds (SWTT) (wet (-35 kPa), medium (-45 kPa), dry (-55 kPa)) whereas the fourth was established according to the current techniques used by the producer which mainly relied on the calculation of crop evapotranspiration (ETc). The experiment was performed over the months of May to August from 2012 to 2015 in 16 rows of 22 Nonpareil almond trees. The rows were subdivided in four blocks of four treatments. Within each treatment of the second block, three tensiometers were installed at three different depths: 25, 50 and 75 cm. Irrigation of each treatment was remotely controlled to never exceed the prescribed SWTTs. The results show that irrigation based on a SWTT of -45 kPa from May to harvest (mid-August) allows saving 20% of water without decreasing yield. These results also indicate that a wet management (-35 kPa) would negatively affect yield just as much as a dry management (-55 kPa).

The second part of the study consisted in adjusting the SWTT of -45 kPa found in part one according to spatiotemporal variability and economic aspects related to soil water tension measurement. The experiment was performed from the end of June to the end of July 2015 in a 30-ha field. The trials included 27 stations of two tensiometers (25 and 50 cm) uniformly located throughout the field within tree rows of the Nonpareil variety. The analyses and the simulations indicate that it would be economically advantageous to use 5 stations and to irrigate when the average of the soil water tensions at 25 and 50 cm of the 5 stations reaches -45 kPa.

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# Avant-Propos

Ce mémoire de maîtrise est divisé en trois chapitres. Le premier chapitre présente une revue de la littérature sur la production d'amandes en général, des méthodes actuelles de gestion d'irrigation dans cette production, ainsi que du fonctionnement d'une régie d'irrigation par tensiométrie.

Le deuxième chapitre et le troisième chapitre sont présentés sous forme d'articles scientifiques rédigés en anglais. Le premier article a été soumis à la revue *Communications in Soil Science and Plant Analysis*. Celui-ci a pour titre « *Soil water tension threshold for almond irrigation* ». Le deuxième article sera quant à lui soumis ultérieurement et s'intitule « *Performance evaluation of soil water tension for managing irrigation at different spatial scale – Case study of an almond orchard in California* ». Je suis le principal auteur de ces articles et les Drs. Jean Caron (Directeur) et Jacques Gallichand (Co-directeur) sont les co-auteurs. Dans le cas du premier article, Guillaume Létourneau est aussi co-auteur. Leurs contributions ont été diverses, de la planification des expériences, à la formulation de suggestions et recommandations sur à l'analyse des données ainsi qu'à la rédaction des articles.

# Introduction générale

Selon toute vraisemblance, l'amande proviendrait de l'Asie Centrale et aurait été présente 4000 ans A.C. (Micke 1996). Les premières petites productions n'auraient cependant été observées que plusieurs centaines d'années plus tard dans des régions très localisées près des côtes méditerranéennes. Ce fruit à coque a été introduit en Amérique avec l'arrivée des premiers colons, mais n'a été cultivé avec succès qu'à partir du milieu du 19$^{e}$ siècle en Californie (Micke 1996).

Aujourd'hui, l'amande est l'une des cultures les plus répandues en Californie avec une superficie totale dépassant les 345 000 hectares (USDA/NASS 2015). En 2014, les revenus d'exportation s'élevaient à 4.5 milliards de dollars (Almond Board of California 2016) correspondant à 25% des exportations agricoles totales de la Californie, permettant ainsi de créer plus d'une centaine de milliers d'emplois directs et indirects (Sumner et al. 2014). De 2013 à 2015, la production mondiale était de l'ordre de 1000 T par année, la majorité de celle-ci provenant de la Californie avec des productions annuelles de 800 à 900 T (Sumner et al. 2014).

L'amande est produite en grande partie dans la Vallée Centrale de la Californie, là où très peu de précipitations surviennent (entre 75 et 305 mm) (CDWR, 2014). Entre les années 1920 et 1970, le pompage de l'eau souterraine a créé dans certaines régions de la vallée des affaissements de terrain atteignant 9 m (Ireland 1986). La création du canal de Delta-Mendota et de l'aqueduc de la Californie ont permis de dévier l'eau de surface au début des années 1970, diminuant le pompage souterrain permettant ainsi de stabiliser la compaction des sols. Malgré tout, à quelques reprises depuis ce temps, la disponibilité de cette eau a été parfois insuffisante faisant réapparaître ce phénomène (Faunt et al. 2015). L'eau provenant de la fonte des neiges de la Sierra Nevada représente environ le tiers de l'eau utilisée en Californie. En date du 20 décembre 2016, seulement 66% de la chute de neige moyenne était tombé (CDWR, 2016). Depuis 2012, la Californie fait face à une sécheresse prolongée (State of California 2016) avec un record obtenu en 2015 (NCEI & NOAA, 2016). Bien que l'affaissement des sols soit un problème important causé par la sécheresse, ce n'est pas le seul. La sécheresse a aussi pour conséquences l’intrusion d’eau saline compromettant la qualité de l’eau souterraine, l’assèchement des puits, l’augmentation des feux de forêt, etc. (USGS 2016).

Considérée comme tolérante à la sècheresse, l’amande est en mesure de survivre avec très peu d’eau soit environ 200 mm (Doll 2014; Torrecillas et al. 1996). Cependant, cette production peut nécessiter jusqu’à 1500 mm d’eau par saison pour obtenir des rendements acceptables (Micke and Kester 1998). Combinant cette forte consommation en eau aux faibles précipitations, les producteurs ont dû graduellement ajuster leur gestion de l’irrigation. Passant de l’irrigation gravitaire à l’irrigation par micro-aspersion et utilisant de nouvelles méthodes proposées par différents chercheurs, les producteurs ont réussi à diminuer leur consommation en eau de 33% tout en produisant de meilleurs rendements durant la dernière décennie (Almond Board of California 2015).

Avec la mise en place d’une centaine de stations météorologiques réparties un peu partout en Californie, les producteurs sont en mesure d’estimer les besoins en eau en calculant l’évapotranspiration de la culture et en faisant un bilan hydrique (Allen et al. 1998; Snyder et al. 1987). Cette méthode, bien qu’étant la plus répandue, ne permet pas de connaître précisément le moment adéquat pour démarrer les irrigations. Plusieurs chercheurs ont donc réuni leur effort pour créer un outil efficace pouvant être utilisé par les producteurs. La majorité de ces méthodes est basée sur des mesures effectuées directement sur la plante (Fereres and Goldhamer 2003; Fulton et al. 2001; Goldhamer, Viveros, and Salinas 2006; Shackel et al. 1997). Bien que n’étant pas limitées à celles-ci, les mesures du potentiel du xylème (qui est devenu le standard) (Fereres and Goldhamer 2003; Fulton et al. 2014; Shackel et al. 1997; Shackel 2007), de la variation de la taille du tronc (Fereres and Goldhamer 2003), du flux de sève (Fuentes et al. 2013; Romero, Muriel, and Garcia 2009) et de la température de la canopée (Dhillon et al. 2014; Maes and Steppe 2012) sont les plus connues et utilisées. Par contre, chacune de ces méthodes possèdent des inconvénients qui ont restreint leur utilisation au niveau commercial (Dhillon et al. 2014; Fulton et al. 2001; Jones 2004; Maes and Steppe 2012; Nortes et al. 2009; Williams and Araujo 2002).

Depuis quelques années, bien que cette méthode ait été proposée déjà en 1961 (Richards and Marsh 1961), la mesure du potentiel matriciel de l’eau du sol en continu a permis diverses percées au niveau de la gestion de l’irrigation dans différentes productions maraichères (Létourneau et al. 2015; Pelletier, Gallichand, and Caron 2013; Périard et al. 2015; Rekika et al. 2014). Pour la production d’amandes, très peu d’information était disponible sur la recommandation d’un seuil de déclenchement de l’irrigation. Taylor (1965) proposait pour les arbres à feuilles caduques respectivement des seuils de -50 kPa et -80 kPa pour des périodes de forte et de faible évapotranspiration. Micke (1996) recommandait quant à lui des seuils de -50 et -70 kPa à une profondeur d’environ 45 à 60 cm. Cependant, ces recommandations ne sont qu’approximatives et ne prennent pas en compte la variabilité spatio-temporelle ainsi que les impacts économiques associés à cette mesure. Elles ne suggèrent aucun nombre de tensiomètres à utiliser ni d’ajustement relié au coût de l’eau. Ainsi, il existe un besoin de recherches supplémentaires sur l’établissement d’une gestion tensiométrique optimale dans la production d’amandes.

L’objectif de ce projet était d’identifier un seuil optimal de l’irrigation basé sur la mesure du potentiel matriciel qui prenne en compte la variabilité spatio-temporelle ainsi que les impacts économiques associés à cette mesure.

# Chapitre 1 : Revue de littérature

## 1.1. Production de l’amande

### 1.1.1. Construction des vergers

Lors de la mise en place d’un verger d’amandiers, plusieurs aspects doivent être considérés. Que ce soit la sélection des variétés, de l’espacement entre les arbres et de leur position, du type de porte-greffe, du type d’émondage et de gestion du sol, du système d’irrigation, des équipements disponibles, tous doivent être choisis en fonction des conditions locales et sont généralement inter-reliés. Pour maximiser les rendements, il est conseillé de planter 50% d’arbres de la variété Nonpareil avec 25% de deux autres variétés dites pollinisatrices (Micke et Kester, 1998). L’espacement entre les arbres généralement utilisé est de 5.5 m x 6.7 m (18’ x 22’), mais peut varier entre 6 m à 9 m (20’ à 30’) (Micke et Kester, 1998). Les arbres sont positionnés soient en carré, en rectangle ou en quinconce. Le cycle de croissance typique des amandes débute par la floraison à la fin février et début mars suivi de la maturation des amandes jusqu’à juin. En juillet, les amandes débutent leur craquage naturel pour permettre l’assèchement. La récolte se fait de la fin juillet jusqu’à octobre, débutant par le brassage mécanique des arbres, suivi du séchage au sol des amandes durant 5 à 10 jours, pour ensuite être récoltées et transformées. De novembre à février, les amandiers tombent en dormance et en profitent alors pour accumuler les nutriments qui seront utilisés l’année suivante (Micke 1996; Micke and Kester 1998).

### 1.1.2. Pollinisation

Actuellement, les variétés plantées en Californie sont en ordre d’importance les Nonpareil (40%), Monterey (13%), Butte/Padre (11%), Carmel (8%), Butte (7%), Fritz (6%), suivi par un ensemble d’autres variétés (15%) (Almond Board of California, 2014). La majorité des variétés d’amandes sont auto-incompatibles pour la pollinisation. Ainsi, une pollinisation croisée entre différentes variétés est requise (Micke et Kester, 1998 ; Geisseler et Horwath, 2014; Micke, 1996). Dépendamment de la variété, la floraison a lieu généralement entre la fin février et le début mars. L’abeille est l’agent principal de transfert de pollen entre les différentes variétés en floraison. Généralement, un objectif de 20 à 40% de production de fruits en fonction du nombre de fleurs est visé. Pour cela, jusqu'à une dizaine de ruches peuvent être positionnées sur une superficie de un hectare en périphérie des champs (Micke et Kester, 1998).

### 1.1.3. Fertilisation et Pesticides

Dans un verger d'amandes, la fertilisation est généralement fournie par le système d'irrigation (Geisseler and Horwath 2014). Pour un amandier mature, il est généralement conseillé de fournir une majorité de la fertilisation en azote durant la formation des fruits entre mars et juin. Il est conseillé que 30% de la fertilisation en azote soit effectuée durant les mois de mars et avril, 40% de mai et juin et 30% de juin à juillet (Brown et al. 2013; Geisseler and Horwarth n.d.; Saa Silva et al. 2012). En ce qui concerne les pesticides, un suivi constant est effectué tout au long du cycle de croissance pour minimiser les problèmes causés par les maladies et les ravageurs. Les principaux insectes ravageurs de l'amande sont le *Amyelois transitella* (Navel Orangeworm), le *Anarsia lineatella* (Peach Twig Borer) et de nombreuses espèces de mites. Les maladies ravageuses sont quant à elles distribuées en deux groupes, soient celles qui attaquent les racines, le tronc et les grosses branches, et celles attaquant les noix, les feuilles et les branches à fruits. Plusieurs autres ravageurs sont aussi présents tels que des nématodes, des oiseaux et des rongeurs (Micke and Kester 1998).

### 1.1.4. Irrigation

Les méthodes d'irrigation utilisées dans la production d'amandes varient entre des méthodes gravitaires, d'aspersion, de microaspersion et de goutte-à-goutte (Micke and Kester 1998). La microaspersion est cependant la plus utilisée (Almond Board of California 2015). Celle-ci consiste en l'installation de conduite d'irrigation dans l'ensemble des rangées d'amandiers dans le champ. Entre chaque arbre, un microasperseur est présent et fourni de l'eau aux arbres pour combler leurs besoins. Le prélèvement de l'eau par les arbres se fait principalement par la zone active des racines se situant dans les premiers 30 cm (Koumanov et al. 1997; Koumanov, Hopmans, and Schwankl 2006; Vrugt, Hopmans, and Simunek 2001). Cependant, les racines se rendent généralement jusqu'à une profondeur maximale de 100 cm pour des vergers matures avec un prélèvement maximal de 0,07 $cm^3cm^{-3}jr^{-1}$ au niveau des premières couches de surface (Allen et al. 1998; Andreu, Hopmans, and Schwankl 1997; San Joaquin River Restoration Program 2015). La méthode de gestion de l'irrigation principale est basée sur l'évapotranspiration des cultures et du bilan hydrique (Doll and Shackel 2015; Micke and Kester 1998; Steduto et al. 2012). Pour déclencher l'irrigation, plusieurs chercheurs ont développé une méthode basée sur la mesure du potentiel du xylème en mi-journée (Doll and Shackel 2015; Fulton et al. 2014; Shackel et al. 1997). Celle-ci est devenue le standard dans la production d'amandes. Cette méthode utilise des équipements tels que la pompe à pression et la bombe à pression (Fulton et al. 2014). D'autres méthodes semblent émerger pour gérer l'irrigation telles que la mesure du flux de sève (Fuentes et al. 2013; Romero et al. 2009), de la température de la canopée (Dhillon et al. 2014; Maes and Steppe 2012) et le rétrécissement maximal du tronc (Fereres and Goldhamer 2003). L'un des aspects importants pouvant parfois régir les besoins d'irrigation est la salinisation des sols. Dans les régions ayant très peu de précipitations, une augmentation de la concentration en sel à la surface peut survenir. La tolérance de l'amande face à la salinité du sol est de 1.5 $dS\ m^{-1}$ (Bernstein, Brown, and Hayward 1956; Brown, Wadleigh, and Hayward 1953; Maas 1990).

### 1.1.5. Cycle physiologique et irrigation de déficit

Bien que l'amandier soit considéré résistant à la sécheresse (Shackel et al., 2011), pour obtenir de bons rendements, une hauteur d'eau allant jusqu'à 1475 mm (58'') est requise (Sanden 2007). En stress hydrique, les feuilles des arbres doivent fermer leurs stomates pour garder leur eau, ce qui diminue par le fait même les échanges gazeux permettant la photosynthèse et ainsi la production de sucres. Ces limitations ont un impact direct sur la croissance végétative et le développement des fruits (Doll and Shackel 2015). Cependant, des recherches ont montré qu'en fonction du stade du cycle de croissance de l'amandier, des impacts différents pouvaient se produire au niveau des rendements (Doll 2014). L'initiation de la floraison et du développement des feuilles a généralement lieu à la fin janvier. Suivent ensuite simultanément la croissance des fruits, l'expansion des feuilles et la croissance des nouvelles branches.

Ces croissances simultanées amènent une compétition au sein des arbres. Donc, si les densités de fleurs et de fruits sont grandes une année, la croissance des nouvelles pousses sera plus faible et diminuera le potentiel de floraison de l'année subséquente (Steduto et al. 2012). De plus, si les réserves en sucres de l'année précédente ne sont pas assez importantes, la nouaison sera plus faible (Esparza et al. 2001). Ainsi, une année très productive sera suivi par une année à rendement plus faible. Trois grands stades de croissance des fruits peuvent être observés. Le premier stade a lieu du début mars jusqu'à la fin avril et correspond à la croissance du tégument et de la cosse. Un stress hydrique durant cette période a pour conséquence une production de plus petits fruits. Le deuxième stade est caractérisé par le durcissement de la cosse et de l'expansion du noyau. Ce stade a généralement lieu du début mai jusqu'à la mi-juin. Un déficit en eau durant cette période réduira la grosseur des fruits et arrêtera la croissance de certains fruits (rabougrissement). Le troisième stade débute vers le début de juin jusqu'à la récolte, soit vers la mi-août. Ce stade est caractérisé par l'augmentation de la matière sèche des noyaux et la différentiation morphologique complète des fruits. Un déficit en eau durant cette période amènera aussi le rabougrissement des fruits, mais aussi la diminution du rendement sec des amandes et une adhésion entre la cosse et la coquille pouvant compliquer la transformation (Doll 2014; Doll and Shackel 2015; Steduto et al. 2012). Par contre, un stress hydrique vers la fin de ce stade n'aurait presqu'aucun effet sur les rendements selon Stewart (2011), et serait même positif pour diminuer les maladies fongiques (Teviotdale, Goldhamer, and Viveros 2001). Après la récolte, a lieu la croissance des bourgeons floraux. Cette période est sensible au stress hydrique, allant jusqu'à réduire de 52% la production de fleurs, 94% de la nouaison et de 73.6% le rendement de l'année suivante (Goldhamer et al. 2006).

## 1.2. Relation sol-plante-atmosphère

### 1.2.1. Évapotranspiration

L'évapotranspiration est la combinaison de deux phénomènes, soient la transpiration des plantes et l'évaporation de surface du sol. L'évapotranspiration est influencée par les paramètres climatiques (la radiation solaire, la température de l'air, l'humidité relative et la vitesse du vent), la culture en place (le type, la variété et son stade de croissance) et le type de gestion utilisé (la salinité, la fertilisation, le type de sol, les ravageurs, etc.). Une distinction doit être faite entre l’évapotranspiration de référence et l’évaporation des cultures. L’évapotranspiration de référence prend en compte seulement le pouvoir évaporatif de l’atmosphère et est indépendante de la culture. L’évapotranspiration des cultures dépend cependant des caractéristiques de la culture et des conditions de gestion et les conditions environnementales. L’évapotranspiration de la culture peut être calculée à l’aide de l’équation 1. Celle-ci dépend de l’évapotranspiration de référence et du coefficient de culture moyen qui dépend entre autres du stade de croissance et de l’assèchement du sol (Allen et al. 1998) :

$$ET_c = K_c ET_o$$

[Éq. 1.1]

Avec,

$\mathrm{ET_c}$ = Évapotranspiration de la culture $[\mathrm{LT^{-1}}]$
$\mathrm{K_c}$ = Coefficient de culture moyen
$\mathrm{ET_o}$ = Évapotranspiration de référence $[\mathrm{LT^{-1}}]$

En Californie, l’évapotranspiration de référence est calculée dans différentes régions à partir de centaines de stations météorologiques appartenant au « California Irrigation Management Information System » (CIMIS) (CDWR, 2015). Ce programme a pour but d’assister les producteurs pour améliorer leur efficacité au niveau de la consommation en eau d’irrigation. Pour la production d’amandes, plusieurs coefficients de culture différents sont proposés dans la littérature (Allen et al. 1998; Girona 2006; Goldhamer and Viveros 2000; Sanden 2009; Steduto et al. 2012; Stevens et al. 2012).

### 1.2.2. Potentiel de l’eau dans le xylème

Pendant la transpiration des arbres, l’eau monte dans l’arbre du sol vers les racines jusqu’aux feuilles, pour atteindre par la suite l’atmosphère. Le flux d’eau à l’intérieur de l’arbre dépend du gradient de potentiel de l’eau entre le sol et l’atmosphère. Lors de l’ouverture des stomates, les échanges gazeux peuvent avoir lieu et un faible potentiel est créé par le fait même à la surface des feuilles. Cela produit ainsi une succion à l’intérieur de l’arbre et permet donc à l’eau d’entrer par les racines. Cette tension dépend principalement de la capacité du sol à fournir l’eau et de la transpiration des feuilles. Différentes techniques ont été mises de l’avant pour mesurer le potentiel de l’eau dans les arbres (potentiel de l’eau dans les feuilles, potentiel de l’eau dans les feuilles avant l’aube, le potentiel de l’eau dans les feuilles à l’ombre et le potentiel de l’eau dans le xylème en mi-journée (Midday Steam Water Potential, MSWP)). Plusieurs recherches ont été effectuées sur la méthode du MSWP permettant ainsi d’avoir beaucoup de connaissances sur le sujet (Fulton et al. 2001). Cette méthode permet une plus grande flexibilité et une moins grande variabilité de mesure. Plusieurs recherches ont d’autant plus montré que le statut du potentiel de l’eau dans les feuilles n’était pas nécessairement directement relié au stress de la plante (Bates and Hall 1981; Jones 1985; Sinclair and Ludlow 1985). Le MSWP est mesuré entre 12h et 16h pour permettre des mesures constantes et au moment où la demande en eau est la plus élevée. Mesurer le MSWP une fois par semaine peut être suffisant pour des vergers utilisant des systèmes d’irrigation localisés (Fulton et al. 2014). Pour mesurer le MSWP, une feuille à l’ombre au bas de la canopée doit être choisie et mise dans un sac (durant un minimum de 10 minutes) pour arrêter la photosynthèse et la transpiration. Ainsi, la feuille s’équilibre avec les branches adjacentes. Par la suite, à l’aide d’une pompe à pression ou d’une bombe à pression, il est possible d’exercer une pression sur la feuille jusqu’à ce que l’eau de la feuille sorte. Cette pression correspond alors au MSWP. Un MSWP entre -1 et -1.4 MPa est généralement conseillé tandis qu’un MSWP inférieur à -2 MPa est considéré critique (Fulton et al. 2014).

### 1.2.3. Productivité en eau

La productivité en eau permet de comparer différentes régies d’irrigation entre elles. Celle-ci correspond à l’efficacité dont la culture réussit à utiliser l’eau pour produire des rendements. Ce paramètre peut donc être influencé par le rendement ou la quantité d'eau utilisée. Plus la productivité est élevée, plus le système est efficace (Cai and Rosegrant 2003). La productivité en eau peut être définie comme étant la valeur d'une production (en quantité ou en argent) par rapport à la consommation en eau associée à cette dite production.

### 1.2.4. Potentiel de l'eau dans le sol

La physique classique reconnaît trois formes d'énergie soient les énergies cinétique, potentielle et interne. Dans le sol, il est possible de négliger l'énergie cinétique de l'eau qui dépend de sa vitesse (très faible) (Hillel 2004) et l'énergie interne (Lal and Shukla 2004). L'énergie potentielle totale de l'eau dans le sol ($\varphi_T$) dépend alors du potentiel matriciel ou de pression ($\varphi_m$ ou $\varphi_p$), du potentiel osmotique ($\varphi_s$) et du potentiel gravitationnel ($\varphi_z$) (Musy and Soutter 1991) (Équation 2).

$$\varphi_T = (\varphi_m \text{ ou } \varphi_p) + \varphi_s + \varphi_z \; [MT^{-2}L^{-1}]$$

[Éq. 1.2]

Dans un sol non saturé, le potentiel de pression est nul et lorsqu'une faible concentration en sel est présente dans la solution du sol, le potentiel osmotique peut être négligé. Le potentiel matriciel correspond aux forces d'adsorption et capillaire induite par la matrice du sol. Le potentiel gravitationnel correspond à la position de l'eau dans la matrice par rapport à un datum.

## 1.3. Régie tensiométrique

Pour mesurer le potentiel matriciel de l'eau dans le sol, il est possible d'utiliser un tensiomètre. Un tensiomètre consiste en un assemblage d'une pierre poreuse connectée au bout d'un tube rempli d'eau tandis qu'à l'autre bout, un instrument mesure la pression. Lorsque le tensiomètre est inséré dans un sol non saturé, l'eau à l'intérieur du tensiomètre à tendance à vouloir sortir du tube et à s'équilibrer avec l'eau de la matrice du sol. Cette succion d'eau vers l'extérieur de la bougie crée ainsi une tension au niveau du capteur qui peut alors être interprété. Dépendamment du type de tensiomètre utilisé, la colonne d'eau présente à l'intérieur de celui-ci doit être prise en compte pour une interprétation adéquate de la mesure fourni par l'équipement sur le potentiel de l'eau au niveau de la matrice du sol. Richards & Marsh (1961) avaient mis de l'avant l'inefficacité des méthodes de bilan hydrique et d'apparence du sol pour gérer l'irrigation étant donné que ces méthodes ne représentaient pas les conditions réelles du moment de la capacité du sol à fournir l'eau. La tension maximale mesurable avec les tensiomètres est de -80 kPa. La tension reste cependant bien supérieure à ce maximum lors d'une régie d'irrigation adéquate. Dans les dernières années, plusieurs projets ont été effectués en lien avec la gestion de l'irrigation à l'aide des tensiomètres, et ce pour différentes cultures (Létourneau et al. 2015; Pelletier et al. 2013; Périard et al. 2015; Rekika et al. 2014). Ces différents projets ont permis dans certains cas d'augmenter la productivité de l'eau sans diminuer les rendements et dans d'autres, d'augmenter les rendements. En ce qui concerne la production d'amandes, bien qu'aucun seuil de tension n'ait été défini clairement, il est suggéré de démarrer les irrigations lorsque la tension des profondeurs sous la surface entre 45 et 60 cm atteint -50 kPa en période de forte évapotranspiration et -70/-80 kPa en faible évapotranspiration (Micke 1996; Taylor 1965)

## 1.4. Variabilité spatio-temporelle du potentiel matriciel

L'uniformité d'application en eau par le système d'irrigation est le premier facteur d'influence de la variabilité spatio-temporelle du potentiel matriciel de l'eau dans le sol (Warrick et Gardner, 1983). Cette variabilité peut s'étendre entre 40 et 95% en fonction du système d'irrigation utilisé (Van Pelt and Wierenga 2001). Le coefficient d'uniformité permet de connaître l'uniformité d'application d'un système d'irrigation. Le coefficient d'uniformité de Christiansen est celui le plus utilisé au niveau des méthodes d'évaluations statistiques des systèmes d'irrigation par aspersion (Christiansen 1942).

$$CU = 100 \times \left(1 - \frac{\sum_{i=1}^{N} |X_i - \bar{X}|}{\bar{X} \cdot N}\right)$$

[Éq. 1.3]

Avec,

$CU$ = Coefficient d'uniformité de Christiansen [%]
$\overline{\mathrm{X}}$ = Moyenne des observations des volumes irrigués [$L^3$]
$X_i$ = Observation du volume irrigué de l'échantillon $i$ [$L^3$]
N = Nombre d'échantillon [-]

La variabilité du potentiel matriciel peut aussi être causée par une variation des propriétés hydrodynamiques du sol à l'échelle d'un champ. Une différence au niveau de la texture et de la structure peut influencer grandement la variation du potentiel matriciel dans l'espace (Greminger, Sud, and Nielsen 1985; Hedley and Yule 2009; Van Pelt and Wierenga 2001; Yeh, Gelhar, and Wierenga 1986). Le dernier aspect influençant la variabilité du potentiel matriciel est le prélèvement de l'eau par les racines de la culture. Celui-ci va varier dans le temps et l'espace en fonction du stade de croissance, du développement des racines, des maladies et des ravageurs, de la fertilisation, de la demande d'évapotranspiration, etc. (Andreu et al. 1997; Hupet and Vanclooster 2002; Koumanov et al. 2006; Van Wesenbeeck, Kachanoski, and Rolston 1988). De manière générale, la distance de dépendance des mesures de tension varie de quelques mètres à une dizaine de mètres (Greminger et al. 1985; Nash, Wierenga, and Butler-Nance 1989; Saddiq et al. 1985; Yeh et al. 1986). La distance de dépendance est définie comme étant la distance au-delà de laquelle il n'y a plus de corrélation entre les points de mesure. Les points de mesure échantillonnés à des distances inférieures à celle-ci sont ainsi corrélés. Dans le cas où la distance d'échantillonnage est supérieur à la distance de dépendance, il peut être considéré que le phénomène observé est distribué de manière aléatoire et donc que les statistiques classiques peuvent être utilisées (Vieira et al. 1983). L'utilisation des géostatistiques pour ce type de mesure nécessite alors beaucoup de points de mesure à l'échelle d'un champ. Typiquement, les mesures du potentiel matriciel suivent une distribution log-normale avec une variance qui a tendance à augmenter lors de l'assèchement du sol (Hendrickx, Wierenga, and Nash 1990; Webster 1966; Yeh et al. 1986).

Dans les dernières années, plusieurs projets ont été effectués en lien avec la gestion de l’irrigation à l’aide des tensiomètres, et ce pour différentes cultures (Létourneau et al. 2015; Pelletier et al. 2013; Périard et al. 2015; Rekika et al. 2014). Ces différents projets ont permis dans certains cas d’augmenter la productivité de l’eau sans diminuer les rendements et dans d’autres, d’augmenter aussi les rendements. En ce qui concerne la production d’amandes, bien qu’aucun seuil de tension n’ait été défini clairement, il est suggéré de démarrer les irrigations lorsque la tension des profondeurs sous la surface entre 45 et 60 cm atteint -50 kPa en période de forte évapotranspiration et -70/-80 kPa en faible évapotranspiration (Micke 1996; Taylor 1965). Cependant, aucune de ces recommandations ne prennent en compte la variabilité spatiotemporelle des propriétés hydrodynamiques du sol et les aspects économiques associées à ce type de prise de mesure. Ainsi, l’intérêt subsiste afin de déterminer un seuil optimal de déclenchement de l’irrigation au niveau de la production d’amandes qui prend en compte l’ensemble de ces paramètres.

## 1.5. Hypothèses et objectifs

En considérant l'ensemble des informations présentées précédemment sur l'importance de la préservation des ressources hydriques ainsi que sur le manque de connaissance sur une régie tensiométrique au niveau de la production de l'amande, cela mène à poser les hypothèses suivantes :

- Une régie de l'irrigation basée sur le déclenchement de l'irrigation par l'atteinte d'un seuil de tension de l'eau dans le sol plus sec (-45 kPa) entraîne une augmentation de la productivité de l'eau sans diminuer les rendements en comparaison avec une régie plus humide (-35 kPa) ou plus sec (-55 kPa);
- Il existe une relation entre la variabilité spatio-temporelle des propriétés hydrodynamiques et les rendements.

Les objectifs de ce projet qui en découlent sont quant à eux:

- d'évaluer l'effet d'un seuil d'irrigation basé sur la mesure du potentiel matriciel de l'eau du sol sur les rendements d'amandes et de la consommation en eau;
- d'ajuster la recommandation d'un seuil d'irrigation basé sur le potentiel matriciel par rapport à la variabilité spatio-temporelle des mesures ainsi que les impacts économiques associés.

## 1.6. Références

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith. 1998. “Crop Evapotranspiration: Guidelines for Computing Crop Requirements.” *Irrigation and Drainage Paper No. 56, FAO* (56):300.

Almond Board of California. 2015. “Almonds and Water 101.”

Almond Board of California. 2016. “California Almond Industry Facts.”

Andreu, L., J. W. Hopmans, and L. J. Schwankl. 1997. “Spatial and Temporal Distribution of Soil Water Balance for a Drip-Irrigated Almond Tree.” *Agricultural Water Management* 35(1–2):123–46.

Bates, L. M. and A. E. Hall. 1981. “Stomatal Closure with Soil Water Depletion Not Associated with Changes in Bulk Leaf Water Status.” *Oecologia* 50:62–65.

Bernstein, L., J. W. Brown, and H. E. Hayward. 1956. “The Influence of Rootstock on Growth and Salt Accumulation in Stone-Fruit Trees and Almonds.” *Proc. Am. Soc. Hort. Sci.* (68):86–95.

Brown, J. W., C. H. Wadleigh, and H. E. Hayward. 1953. “Foliar Analysis of Stone Fruit and Almond Trees on Saline Substrates.” *Proc. Am. Soc. Hort. Sci.* (61):49–55.

Brown, P., S. Saa, S. Muhammad, and B. Sanden. 2013. “Development of Leaf Sampling and Interpretation Methods and Nutrient Budget Approach to Nutrient Management in Almond.” *Western Nutrient Management Conference* 10:43–48.

Cai, X. and M. W. Rosegrant. 2003. “World Water Productivity: Current Situation and Future Options.” *World Water* 163–78.

California Department of Water Resources. 2014. “Water Year 2014 Ends as 3rd Driest in Precipitation.”

California Department of Water Resources. 2016. “Statewide Summary of Snow Water Content.”

Christiansen, J. E. 1942. “Irrigation by Sprinkling.”

Dhillon, R., V. Udompetaikul, F. Rojo, and J. Roach. 2014. “Detection of Plant Water Stress Using Leaf Temperature and Microclimatic Measurements in Almond, Walnut, and Grape Crops.” *Transactions of the ASABE* 57(1):297–304.

Doll, D. 2014. “Impacts Of Drought On Almond Production.” *Western Fruit Grower - California Nut Report* 134(7):8–10.

Doll, D. and K. Shackel. 2015. “Drought Management for California Almonds.” *ANR Publication 8515* 1–10.

Esparza, G., T. M. DeJong, S. A. Weinbaum, and I. Klein. 2001. “Effects of Irrigation Deprivation during the Harvest Period on Ield Determinants in Mature Almond Trees.” *Tree physiology* 21(14):1073–79.

Faunt, C. C., M. Sneed, J. Traum, and J. T. Brandt. 2015. "Water Availability and Land Subsidence in the Central Valley, California, USA." *Hydrogeology Journal* 24(3):675–84.

Fereres, E. and D. A. Goldhamer. 2003. "Suitability of Stem Diameter Variations and Water Potential as Indicators for Irrigation Scheduling of Almond Trees." *Journal of Horticultural Science and Biotechnology* 78(2):139–44.

Fuentes, S., M. Mahadevan, M. Bonada, M. A. Skewes, and J. W. Cox. 2013. "Night-Time Sap Flow Is Parabolically Linked to Midday Water Potential for Field-Grown Almond Trees." *Irrigation Science* 31(6):1265–76.

Fulton, A., R. Buchner, B. Olson, L. Schwankl, C. Gilles, N. Bertagna, J. Walton, K. Shackel. 2001. "Rapid Equilibration of Leaf and Stem Water Potential under Field Conditions in Almonds, Walnuts, and Prunes." *HortTechnology* 11(4):609–15.

Fulton, A., J. Grant, R. Buchner, and J. Connell. 2014. "Using the Pressure Chamber for Irrigation Management in Walnut, Almond, and Prune." *ANR Publication 8503* 1–27.

Geisseler, D. and W. R. Horwarth. n.d. "Almond Nitrogen Fertilization Guidelines." *Fertilizer Research and Education Program, California Department of Food and Agriculture*.

Geisseler, D. and W. R. Horwath. 2014. "Almond Production in California." *Fertilizer Research and Education Program* 1–3.

Girona, J. 2006. "La Respuesta Del Cultivo Del Almendro Al Riego." *Vida Rural* (Septiembre):12–16.

Goldhamer, D. A. and M. Viveros. 2000. "Effects of Preharvest Irrigation Cutoff Durations and Postharvest Water Deprivation on Almond Tree Performance." *Irrigation Science* 19(3):125–31.

Goldhamer, D. A., M. Viveros, and M. Salinas. 2006. "Regulated Deficit Irrigation in Almonds: Effects of Variations in Applied Water and Stress Timing on Yield and Yield Components." *Irrigation Science* 24:101–14.

Greminger, P. J., Y. K. Sud, and D. R. Nielsen. 1985. "Spatial Variability of Field-Measured Soil-Water Characteristics." *Soil Science Society of America Journal* 49(5):1075–82.

Hedley, C. B. and I. J. Yule. 2009. "Soil Water Status Mapping and Two Variable-Rate Irrigation Scenarios." *Precision Agriculture* 10(4):342–55.

Hendrickx, J. M. H., P. J. Wierenga, and M. S. Nash. 1990. "Varibility of Soil-Water Tension and Soil-Water Content." *Agricultural Water Management* 18(2):135–48.

Hillel, D. 2004. "Water Content and Potential." Pp. 93–125 in *Introduction to Environmental Soil Physics*.

Hupet, F. and M. Vanclooster. 2002. "Intraseasonal Dynamics of Soil Moisture Variability within a Small Agricultural Maize Cropped Field." *Journal of*

*Hydrology* 261(1–4):86–101.

Ireland, R. L. 1986. "Land Subsidence in the San JoaquinValley, California, as of 1983." *US Geol SurvWater Resour Invest* (Rep 85-4196):50.

Jones, H. G. 1985. "Physiological Mechanisms Involved in the Control of Leaf Water Status: Implications for the Estimation of Tree Water Status." *Acta Horiculturae* 171(Water Relations in Fruit Crops):291–96.

Jones, H. G. 2004. "Irrigation Scheduling: Advantages and Pitfalls of Plant-Based Methods." *Journal of Experimental Botany* 55(407):2427–36.

Koumanov, K. S., J. W. Hopmans, L. J. Schwankl, L. Andreu, and A. Tuli. 1997. "Application Efficiency of Micro-Sprinkler Irrigation of Almond Trees." *Agricultural Water Management* 34(3):247–63.

Koumanov, K. S., J. W. Hopmans, and L. W. Schwankl. 2006. "Spatial and Temporal Distribution of Root Water Uptake of an Almond Tree under Microsprinkler Irrigation." *Irrigation Science* 24(4):267–78.

Lal, R. and M. K. Shukla. 2004. *Principles of Soil Physics*. edited by  inc. Marcel Dekker.

Létourneau, G., J. Caron, L. Anderson, and J. Cormier. 2015. "Matric Potential-Based Irrigation Management of Field-Grown Strawberry: Effects on Yield and Water Use Efficiency." *Agricultural Water Management* 161:102–13.

Maas, E. V. 1990. "Crop Salt Tolerance." *Agricultural Salinity Assessment and Management* American S(71).

Maes, W. H. and K. Steppe. 2012. "Estimating Evapotranspiration and Drought Stress with Ground-Based Thermal Remote Sensing in Agriculture: A Review." *Journal of Experimental Botany* 63(13):4671–4712.

Micke, W. C. 1996. *Almond Production Manual*. UCANR Publications.

Micke, W. C. and D. E. Kester. 1998. "Almond Growing in California." *Acta Horticultura* (470):21–28.

Musy, A. and M. Soutter. 1991. *Physique Du Sol*. 1st ed. edited by Presse polytechniques et universitaires romandes.

Nash, M. S., P. J. Wierenga, and A. Butler-Nance. 1989. "Variation in Tension, Water Content, and Drainage Rate Along a 91-M Transect." *Soil Science* 148(2):94–101.

National Centers for Environmental Information and National Oceanic and Atmospheric administration. 2016. "Climatogical Ranking."

Nortes, P. A., A. Baille, G. Egea, M. M. González-Real, and R. Domingo. 2009. "Comparison of Almond Tree Transpiration Determined by Sap Flow Measurements and Lysimetry." *Acta Horticulturae* 846:359–66.

Pelletier, V., J. Gallichand, and J. Caron. 2013. "Effect of Soil Water Potential Threshold for Irrigation on Cranberry Yield and Water Productivity." *Transactions of the American Society of Agricultural and Biological*

*Engineers* 56(6):1325–32.

Van Pelt, R. S. and P. J. Wierenga. 2001. “Temporal Stability of Spatially Measured Soil Matric Potential Probability Density Function.” *Soil Science Society of America Journal* 65(3):668.

Périard, Y., J. Caron, J. Lafond, and S. Jutras. 2015. “Root Water Uptake by Romaine Lettuce in a Muck Soil : Linking Tip Burn to Hydric Deficit.” *Vadose Zone Journal* 14(6):13.

Rekika, D., J. Caron, G. Théroux-Rancourt, J. Lafond, S. Gumiere, S. Jenni, A. Gosselin. 2014. “Optimal Irrigation for Onion and Celery Production and Spinach Seed Germination in Histosols.” *Agronomy Journal* 106(3):981.

Richards, S. J. and A. W. Marsh. 1961. “Irrigation Based on Soil Suction Measurements.” *Soil Science Society of America Proceedings* 25(1):65–69.

Romero, R., J. L. Muriel, and I. Garcia. 2009. “Automatic Irrigation System in Almonds and Walnuts Trees Based on Sap Flow Measurements.” *Acta Horticulturae* 846:135–42.

Saa Silva, S., S. Muhammad, B. Sanden, E. Laca, and P. Brown. 2012. “Almond Early-Season Sampling and In-Season Nitrogen Application Maximizes Productivity, Minimizes Loss.” *Almond Board of California* 1–9.

Saddiq, M. H., P. J. Wierenga, J. M. H. Hendrickx, and M. Y. Hussain. 1985. “Spatial Variability of Soil Water Tension in an Irrigated Soil.” 126–32.

San Joaquin River Restoration Program. 2015. “Almond Root Zone Study Plan Phase 1.” *San Joaquin River Restoration* 1–64.

Sanden, B. 2007. “Fall Irrigation Management in a Drought Year for Almonds.” *Kern Soil and Water* 1–6.

Sanden, B. 2009. “Managing Mid-Season Almond Irrigation , Hull Rot & Regulated Deficit Irrigation.” 1–5.

Shackel, K. A. et al. 1997. “Plant Water Status as an Index of Irrigation Need in Deciduous Fruit Trees.” *HortTechnology* 7(1):23–29.

Shackel, K. A. 2007. “Water Relations of Woody Perennial Plant Species.” *Journal International des Sciences de la Vigne et du Vin* 41(3):121–29.

Sinclair, T. R. and M. M. Ludlow. 1985. “Who Taught Plants Thermodynamics? The Unfulfilled Potential of Plant Water Potential.” *Australian Journal of Plant Physiology* 12:213–17.

Snyder, R. L., B. J. Lanini, D. A. Shaw, and W. O. Pruit. 1987. “Using Reference Evapotranspiration (ET0) and Crop Coefficients to Estimate Crop Evapotranspiration (Etc) for Trees and Vines” edited by U. of California.

State of California. 2016. “California Drought.”

Steduto, P., T. C. Hsiao, E. Fereres, and D. Raes. 2012. “Crop Yield Response to Water.” *FAO Irrigation and Drainage Paper* (66):505.

Stevens, R. M., C. M. Ewenz, G. Grigson, and S. M. Conner. 2012. "Water Use by an Irrigated Almond Orchard." *Irrigation Science* 30(3):189–200.

Stewart, W. L., A. E. Fulton, W. H. Krueger, B. D. Lampinen, and K. A. Shackel. 2011. "Regulated Deficit Irrigation Reduced Water Use of Almonds without Affecting Yield." *California Agriculture* 65(2):90–95.

Sumner, D. A., W. A. Matthews, J. Medellín-azuara, and A. Bradley. 2014. "The Economic Impacts of the California Almond Industry." 53.

Taylor, S. A. 1965. "Managing Irrigation Water on the Farm." *Transactions of the ASAE* 8(3):433–36.

Teviotdale, B. L., D. A. Goldhamer, and M. Viveros. 2001. "Effects of Deficit Irrigation on Hull Rot Disease of Almond Trees Caused by Monilinia Fructicola and Rhizopus Stolonifer." *Plant Disease* 85(4):399–403.

Torrecillas, A., J. J. Alarcón, R. Domingo, J. Planes, and M. J. Sánchez-Blanco. 1996. "Strategies for Drought Resistance in Leaves of Two Almond Cultivars." *Plant Science* 118(2):135–43.

USDA/NASS. 2015. *Agricultural Statistics 2015*.

USGS. 2016. "Drought Impacts."

Vieira, S. R., J. L. Hatfield, D. R. Nielsen, and J. W. Biggar. 1983. "Geostatistical Theory and Application to Variability of Some Agronomical Properties." *Hilgardia* 51(3)(3):1–75.

Vrugt, JA, JW Hopmans, and Jirka Simunek. 2001. "Calibration of a Two-Dimensional Root Water Uptake Model." *Soil Science Society of America Journal* 65(4):1027–37.

Warrick, A. W. and W. R. Gardner. 1983. "Crop Yield as Affected by Spatial Variations of Soil and Irrigation." *Water Resources Research* 19(1):181–86.

Webster, R. 1966. "The Measurement of Soil Water Tension in the Field." *New Phytologist* 65(2):249–58.

Van Wesenbeeck, I. J., R. G. Kachanoski, and D. E. Rolston. 1988. "Temporal Persistence of Spatial Patterns of Soil Water Content in the Tilled Layer Under a Corn Crop." *Soil Science Society of America Journal* 52(4):934.

Williams, L. E. and F. J. Araujo. 2002. "Correlations among Predawn Leaf, Midday Leaf, and Midday Stem Water Potential and Their Correlations with Other Measures of Soil and Plant Water Status in Vitis Vinifera." *J. Amer. Soc. Hort. Sci.* 127(3):448–54.

Yeh, T. C. J., L. W. Gelhar, and P. J. Wierenga. 1986. "Observations of Spatial Variability of Soil-Water Pressure in a Field Soil." *Soil Science* 142(1):7–12.

# Chapitre 2 : Soil water tension threshold for almond irrigation - Potentiel matriciel seuil de l’eau du sol en production d’amandes.

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# Résumé

L'impact du seuil de départ de l'irrigation sur la consommation en eau et les rendements d'amandiers matures a été déterminé à l'aide de quatre différents traitements d'irrigation dans un verger commercial situé dans la Vallée Centrale de la Californie qui ont été mis en place de 2012 à 2015. Trois traitements étaient basés sur des mesures en temps réel du potentiel matriciel de l'eau du sol et un quatrième était basé sur la gestion typique du producteur utilisant l'évapotranspiration de la culture. Cette étude a été effectuée pour déterminer la possibilité d'utiliser la tension du sol pour gérer l'irrigation ainsi que pour déterminer une tension seuil de déclenchement d'irrigation. Les traitements basés sur la tension ont été définis selon trois différents niveaux de stress, soient humide (-35 kPa), modéré (-45 kPa) et sec (-55 kPa). Durant les quatre années d'étude, le traitement du producteur a utilisé 20 % d'eau d'irrigation de plus que les traitements humide et modéré, et 30 % de plus que le traitement sec. Il n'y avait aucune différence significative au niveau du rendement vendable entre le traitement du producteur et le traitement modéré, tandis qu'une diminution significative de 10 % a été observée pour les traitements humide et sec par rapport au traitement modéré. Le traitement modéré permet une réduction de la consommation en eau sans diminuer la productivité par rapport à la méthode utilisée par le producteur. De plus, les résultats ont montré qu'un régime d'irrigation humide soutenu influence négativement la production d'amandes autant que l'irrigation de déficit.

Mots clés: Amandes, irrigation, potentiel matriciel, évapotranspiration, potentiel du xylème, déficit de pression de vapeur de la feuille, consommation en eau.

# Abstract

Yield responses and water consumption of mature almond trees were quantified from 2012 to 2015 for four different irrigation strategies in a commercial orchard located in San Joaquin Valley in California. Three treatments were based on real-time soil water tension threshold measurements (SWTT) and another according to the management practice currently used by the grower; that is using estimated crop evapotranspiration (ETc). The objective of this study was to examine the possibility of using SWTT in irrigation scheduling and determined an optimal value for irrigation triggering. The SWTT treatments were based on three different stress levels: wet (-35 kPa), medium (-45 kPa) and dry (-55 kPa). Through these years, the grower treatment used about 20% more water than the wet and medium irrigation treatments, and over 30% more water than the dry treatment. There was no significant difference between marketable yield of the grower and that of the medium treatment. However, there was a 10% significant yield reduction for the wet and dry treatments compared to the medium treatment. The medium treatment allowed water saving without decreasing productivity. Moreover, results showed that the continuous wet regime and the deficit irrigation regime had negatively influenced almond production.

Keywords: Almonds, irrigation, soil water matric potential, evapotranspiration, midday stem water potential, leaves vapour pressure deficit, water consumption.

# Introduction

Almonds [*Prunus dulcis* (Mill.) D.A. Webb] are produced on more than 345,000 hectares in California, mainly in the Central Valley (USDA/NASS 2015). This state produces almost 100% of the country's almonds and 80% of the world almonds (Almond Board of California 2016). This industry creates directly or indirectly about 104,000 jobs and has an annual economic output of about $21.5 billion (Sumner et al. 2014). Even if this production is drought resistant (Torrecillas et al. 1996), it requires approximately 600 to 1500 mm of water to have acceptable yields (Micke and Kester 1998). In California, agriculture uses nearly 80% of the dedicated freshwater (Canessa, Green, and Zoldoske 2012). Excessive pumping causes lowering of groundwater, intrusion of saline water and drying of wells (Croyle et al. 2014). Producers are under increasing social pressure to reduce water uptake. The amount of water required by almond trees cannot be supported by the current levels of precipitation (75 to 305 mm depending on the area), a situation compounded by the drought of the last ten years (California Department of Water Resources 2014). Nowadays, 70% of the producers use micro-irrigation and thus almost 33% less water than in the past (Almond Board of California 2015). Three main classes of irrigation scheduling exist which are based on climatic, plant or soil water measurements. The water balance method is the most commonly used, but it needs good local estimate of crop evapotranspiration which depends on the canopy, irrigation method, climate and crop development (Allen et al. 1998). This method provides a good approximation of how much water is needed, but not when it is required. To help determine the triggering of irrigation, researchers developed several methods using tree water status measurements (Fereres and Goldhamer 2003; Fulton et al. 2001; Goldhamer, Viveros, and Salinas 2006; Shackel et al. 1997). Midday stem water potential (MSWP) has become the new standard irrigation management (Fereres and Goldhamer 2003; Fulton et al. 2014; Shackel 2007; Shackel et al. 1997). However, this technique needs continuous monitoring which is time consuming (Fulton et al. 2001) and requires well-trained technicians (Williams and Araujo 2002). Also, this method can hardly be used to automate irrigation (Jones 2004). Thermal sensing represents a promising alternative to detect plants stress, especially with the rapid evolution of unmanned aerial vehicle technology (Maes and Steppe 2012). Dhillon et al. (2014) have also developed a set of mobile sensors which measure leaf temperature and climatic variables to predict water stress. However, improvements are required before any of these techniques can be fully operational and automated (Dhillon et al. 2014; Maes and Steppe 2012). Regarding soil water measurements, several limitations have been put forward by many researchers (Fereres 1996; Naor 2006), like measurement variability due to soil heterogeneity, cost limitation and calibration requirements. However, these soil water measurement can be fully automated and easily integrated to provide timely scheduling of irrigation (Hodnett et al. 1990; Moutonnet, Brandy-Cherrier, and Chambon 1981). Tensiometers are used to measure soil water potential and have shown to be very useful in timing irrigation (Richards and Marsh 1961). Recent technologies based on real-time soil matric potential measurement have led to increase water productivity without decreasing yield in cranberries (Pelletier, Gallichand, and Caron 2013) and strawberries (Létourneau et al. 2015). This technology has also helped increasing yields for celery and onion, spinach germination (Rekika et al. 2014) and preventing tip burn of romaine lettuce in muck soil (Périard et al. 2015). Due to a lack of information in almond production, additional research is needed to develop irrigation scheduling based on soil water tension. The objective of this study was to evaluate the effect of soil water matric potential irrigation thresholds on almond yield and water consumption.

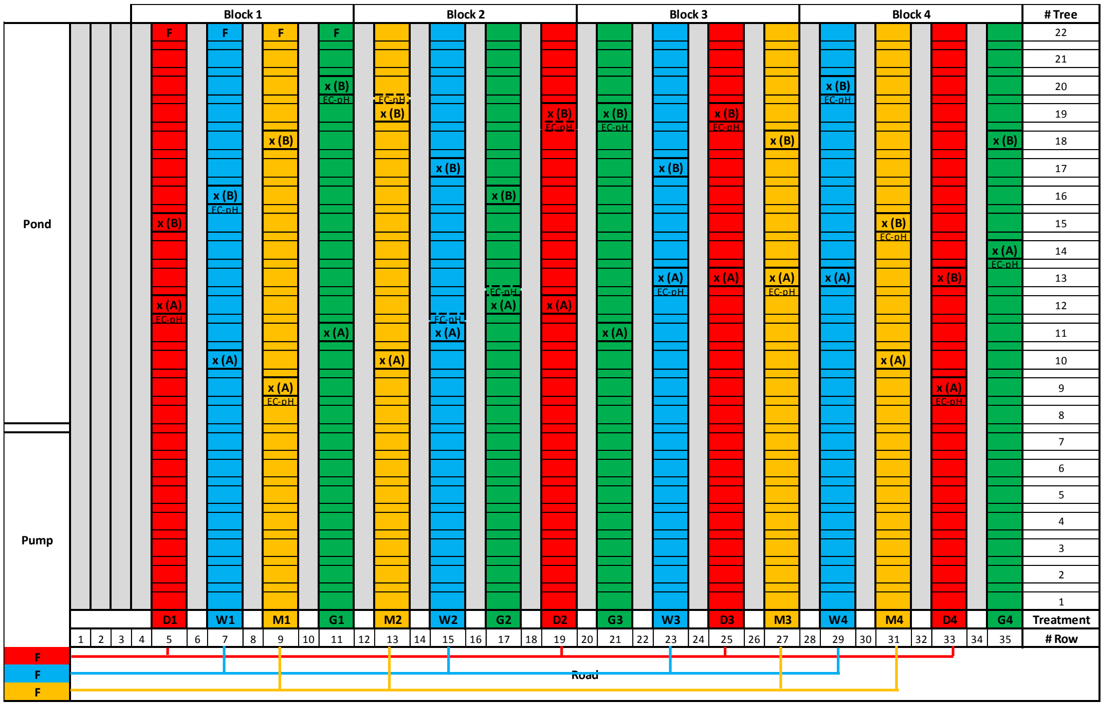
## 2.1. Material and methods

### 2.1.1. Experimental site

The experiment was conducted from 2012 to 2015 in a mature almond tree orchard (*Prunus dulcis* (Mill.) D.A. Webb) located in Shafter, California (United States) (354,346° N, 119.2067 ° W) just outside Bakersfield in the San Joaquin Valley. The experiment was performed from April 3rd to August 19th in 2012, from April 2nd to August 15th in 2013, from April 1st to August 8th in 2014 and from May 18th to August 8th in 2015. The site is characterized by a Milham sandy loam soil (O'Green et al. 2016) with the Nonpareil almond variety on alternate rows. The plot was located on a 1.2-ha section of a 30.4-ha field with tree spacings of 5.5 m (in-row) × 7.3 m (inter-row). Trees were irrigated by a 12-jets micro-sprinklers (58 L/h @ 0.17–0.24 MPa, Gironet$^{TM}$, Netafim, CA, USA) irrigation system placed midway between trees in the tree row with a wetted radius of approximately 2 m. The soil surface was maintained free of weeds during the experiment.

## 2.1.2. Experimental Design

The experimental layout was a completely randomized block design. The trials included 16 rows of 22 trees (Nonpareil variety) for a total of 32 rows. Each block contained alternately different varieties separated between treatments by a non-instrumented row. Rows were separated in 4 blocks of 4 treatments: wet, medium, dry and grower. Two trees were used per replicate to monitor tree water stress (Figure 2.1.).



| Legend | |
|---|---|
| x | Trees for MSWP and VPDleaf measurements |
| A,B | Sampled trees for yield |
| F | Flowmeters |
| - - - | Tensiometers |
| EC-pH | EC-PH samples |

| Treatments | |
|---|---|
| G | Grower (Etc) |
| W | Wet (-35 kPa) |
| M | Medium (-45 kPa) |
| D | Dry (-55 kPa) |

**Figure 2.1. Experimental design.**

### 2.1.3. Climatic, soil and tree water data

In each treatment of block 2, three tensiometers (connected to a TX3 wireless station, Hortau Inc., Québec, Canada) were installed at three different depths: 25 cm, 50 cm and 75 cm. Soil water tension (SWT) was continuously collected at 15-minute intervals and sent to a web server (Irrolis, www.hortau.com, Hortau Inc., Québec, Canada). These depths were chosen after observations on site: roots were not present under 75 cm and most of them were concentrated in the 0 to 50 cm depth. Also, an oxidized layer was observed at about 75 cm which shows that there was not much water movement below that depth. Several studies showed that active root water uptake is in the upper soil layer (0–30 cm) and decreases significantly below that depth, and that total root zone is limited to the 90–100 cm soil depth (Andreu, Hopmans, and Schwankl 1997; Koumanov et al. 1997; Koumanov, Hopmans, and Schwankl 2006; Vrugt, Hopmans, and Simunek 2001). This explains the choice of 25, 50 and 75 cm depths instead of 45, 60 and 90 cm which are recommended (Hortau Inc., Québec, Canada). Tensiometers were installed at mid-distance of the micro-sprinkler wetted radius at 45° from the tree row. Only one station per block was used due to cost limitations. Irrigation was controlled to never decrease under the soil water tension threshold (SWTT) of each treatment: -35 kPa (wet), -45 kPa (medium) and -55 kPa (dry). SWTT values were determined by taking the average of the 25 and 50 cm tensiometers. Irrigation was activated by instrumented valves and pump (Hortau Inc., Québec, Canada) when the threshold was attained and stopped when the wetting front reached the 75 cm tensiometer (when the SWT at 75 cm began to increase). The grower treatment (grower) was controlled by the producer using crop evapotranspiration (ETc) (758, 754, 685 and 450 mm from 2012 to 2015).

Climatic data were measured by an automated weather station (Hortau Inc., Québec, Canada) directly installed on site. Reference evapotranspiration (ETo) was calculated using Penman-Monteith equation (Allen et al. 1998). For comparison purposes, we used crop coefficient (Kc) values of Allen et al. (1998), (Goldhamer and Viveros 2000), Goldhammer (Steduto et al. 2012) and Sanden (Sanden 2009) to estimate ETc. Water use was different as the length of the period of analysis changed for each year.

Therefore, %ETc calculated as the sum of irrigation water use and rainfall divided by ETc was used to compare water use for each year.

Midday stem water potential (MSWP) was measured weekly (Fulton et al. 2014) on the same two trees in each plot using a pump-up chamber (PMS Instrument Company, Albany, OR, USA) and a pressure chamber (Soilmoisture Equipment Corp., Santa Barbara, CA, USA). Stem water potential bags (PMS Instrument Company, Albany, OR, USA) were installed on shaded leaves on a lower branch near the trunk at least 10 minutes before measurements (Fulton et al. 2001). Measurements were made just after excision of the leaves. Before installation of stem water potential bags, leaf temperature was measured with an infrared thermometer (IR 1000, Klein Tools, IL, USA). Shaded leaves are better suited to relate plant water status and leaf temperature measurement (Dhillon et al. 2014). Leaf temperature was coupled to relative humidity measured by the weather station to estimate leaf vapor pressure deficit (VPDleaf). Plant measurements were collected from beginning of May to harvest in mid-August.

In 2012, several undisturbed soil sample cylinders (8.2 cm diameter by 5.5 cm height) were collected at depths of 25 and 50 cm to determine bulk density, saturated hydraulic conductivity, and soil water retention curves (WRC). Vertical constant head soil core method (Reynolds 2008) and the multistep outflow method (Dane and Hopmans 2002) in Tempe cells (Soil Moisture Equipment Corp., USA) were used to measure saturated hydraulic conductivity and WRC. Hydraulic parameters were fitted with HYDRUS-1D (PC-Progress, Prague, Czech Republic). Textural classes were determined from particle size analyses of disturbed samples taken in 2011. At the beginning and the end of each season, disturbed soil samples were analyzed in all plots to monitor electrical conductivity (EC) and pH at 25 and 50 cm using soil saturated extract (SSE) method (Brown 1988). Figure 2.2 presents the water retention curve (WRC) and the unsaturated hydraulic conductivity curve at the 25 and 50 cm depths. Textural analysis showed that the soil is a fine sandy loam for both depths which is consistent with O’Green et al. (2016). Saturated hydraulic conductivity was lower at 25 than 50 cm. Except in 2012 at 50 cm in the grower treatment, soil salinity never exceeded the salt tolerance of 1.5 dS m$^{-1}$ (Bernstein, Brown, and Hayward 1956; Brown, Wadleigh, and Hayward 1953; Maas 1990) (Table 2.I).

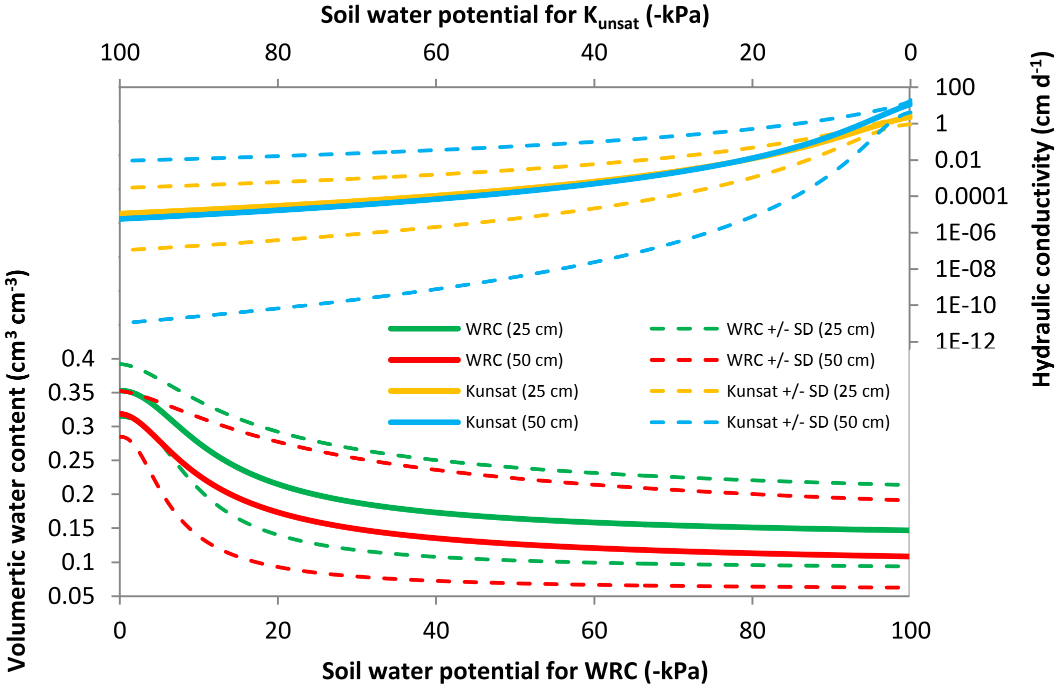


**Figure 2.2. Volumetric water content and unsaturated hydraulic conductivity related to soil water potential. Solid and dashed lines respectively represent mean and standard deviation (SD) values and 25-cm ($N_{25\text{-cm}}$=7) and 50-cm ($N_{50\text{-cm}}$=6) depth.**

**Table 2.I : Soil electrical conductivity (EC) and pH (mean ± standard error (number of samples)) at 25 and 50 cm for each irrigation treatment in 2012, 2013 and 2015**

| | | EC (dS m$^{-1}$) | | | pH | | |
|---|---|---|---|---|---|---|---|
| **Treatment** | **Soil Depth (cm)** | **2012** | **2013** | **2015** | **2012** | **2013** | **2015** |
| **Grower** | **25** | 0.31 ± 0.01 (6) | 0.56 ± 0.04 (24) | 0.58 ± 0.07 (16) | 7.86 ± 0.18 (6) | 6.99 ± 0.05 (24) | 7.46 ± 0.07 (16) |
| | **50** | 2.50 ± 0.03 (3) | 0.58 ± 0.07 (20) | 0.54 ± 0.03 (16) | 7.43 ± 0.04 (3) | 7.17 ± 0.05 (20) | 7.63 ± 0.08 (16) |
| **Wet** | **25** | 0.29 ± 0.02 (9) | 0.63 ± 0.05 (24) | 0.34 ± 0.04 (16) | 7.87 ± 0.02 (9) | 6.95 ± 0.06 (24) | 7.46 ± 0.09 (16) |
| | **50** | - ± - (-) | 0.58 ± 0.06 (24) | 0.42 ± 0.04 (16) | - ± - (-) | 7.03 ± 0.05 (24) | 7.64 ± 0.10 (16) |
| **Medium** | **25** | 0.26 ± 0.01 (9) | 0.75 ± 0.11 (20) | 0.42 ± 0.03 (16) | 7.81 ± 0.07 (9) | 6.97 ± 0.06 (20) | 7.15 ± 0.07 (16) |
| | **50** | 0.17 ± 0.00 (3) | 0.64 ± 0.07 (25) | 0.47 ± 0.05 (16) | 8.08 ± 0.02 (3) | 6.96 ± 0.06 (25) | 7.62 ± 0.11 (16) |
| **Dry** | **25** | 0.36 ± 0.07 (9) | 0.49 ± 0.04 (28) | 0.50 ± 0.06 (16) | 7.72 ± 0.17 (9) | 7.02 ± 0.07 (28) | 7.27 ± 0.09 (16) |
| | **50** | - ± - (-) | 0.63 ± 0.09 (23) | 0.56 ± 0.06 (16) | - ± - (-) | 7.13 ± 0.06 (23) | 7.59 ± 0.10 (16) |

### 2.1.4. Yield Measurements

At harvest, two trees per replicate were mechanically shaken by commercial equipment. Immediately after, almonds were raked in the average area (5.5 m by 7.3 m), picked and weighted. Subsamples (~300 almonds) were cracked, sorted and dried at 80°C until equilibrium weight to analyze marketable yield. Additional yield values were obtained from neighboring plots using the same wireless tensiometer technology with producer historical data from 2011 to 2014. These yield values were the average for the Nonpareil variety of a same field monitored with the tensiometer. We related in-season (May to mid-August) average of SWTT at 25-50 cm to these average yields to extend response values.

### 2.1.5. Water Use

During the monitoring period, rotary flowmeters were installed to measure water applied with an accuracy of ±1.5% (IP80-Series, Seametrics, WA, USA) and ±3% (TM Series, GPI, KS, USA). Flowmeters measured all water applied to the crop: that used for treatments and that used during fertilizer and grower applications. SWTT treatment flowmeters were installed at the beginning of the irrigation line, after the instrumented valves. Flowmeters measuring water coming through fertigation and grower irrigation were installed at the end of the first block. Water use from SWTT treatments was continuously recorded every 15 minutes (Hortau Inc., Québec, Canada) and weekly for those from fertilization and grower applications. SWTT treatments were connected to grower irrigation system through manual valves to allow the same fertilization application in all treatments. The valves were opened before and closed after the applications by a grower technician. Irrigation was taken over by the producer two weeks before harvest to allow the same preharvest management in all treatments.

### 2.1.6. Statistical Analysis

Analyses of variance (ANOVA) were made with the SAS software (SAS Institute Inc., Cary, USA) using the GLM procedure. Least significant differences (LSD) were calculated to compare treatment means. Statistical comparisons were significant at $P < 0.05$. Statistical analysis and relations were determined from mean values of seasonal MSWP, VPDleaf, SWTT and %ETc. The boundary approach (Webb R.A. 1972) was used to approximate optimum values of MDSWP, VPDleaf, SWTT and %ETc according to almond yield. The boundary data were found by using the Schnug approach (Schnug, Heym, and Achwan 1996) without excluding outliers and without lifting data. Polynomial and spline interpolations were used on the boundary data to generate the boundary lines. The boundary line analysis was performed using the R software (The R Development Core Team, 2008).

## 2.2. Results and discussion

### 2.2.1. Tree and soil water status

Tree stresses were less important at the beginning of the season. There still had water stocked in the soil from winter rain, less evapotranspiration demand and more water coming from fertigation. Stresses were mainly observable from early June to harvest, when ET demand peaked.

Table 2.II presents cumulative water, SWTT and the number of irrigations for each year of the experiment. Figure 2.3 presents the cumulative water (ETc, Rainfall, and irrigation water for each treatments) and mean SWT of 25 and 50 cm depth tensiometers for each seasons. During the monitoring period, the grower, the wet and the medium treatments received more water than the dry treatment. Over the four years, the grower treatment used about 600 mm more irrigation water than the wet and the medium treatments, and about 950 mm more than the dry treatment. The medium treatment received amounts of water similar to the wet treatment. That could be explained by a lower growth of the wet treatment caused by root asphyxia, which would result in lower water consumption. In 2013, the wet treatment received less water because of algae clogging in the lateral filter.

**Table 2.II : Cumulative water, soil water tension threshold (SWTT) and the number of irrigation for each year and irrigation treatment**

| | Treatment | 2012† | 2013 | 2014 | 2015 | Mean 2012-2015 |
|---|---|---|---|---|---|---|
| **Cumulative water (%ETc (mm))** | **Grower** | 120 (865)‡ | 103 (767) | 106 (714) | 118 (516) | 112 |
| | **Wet** | 79 (558) | 62 (461) | 95 (638) | 124 (545) | 90 |
| | **Medium** | 82 (578) | 68 (500) | 106 (712) | 118 (515) | 94 |
| | **Dry** | 51 (340) | 56 (416) | 95 (635) | 114 (500) | 79 |
| | **ETc** | (758) | (754) | (685) | (450) | - |
| | **Rainfall** | (44) | (9) | (14) | (15) | - |
| **SWTT ± SD (kPa)§** | **Grower (ETc)** | -30.0 ± 19.8 | -42.2 ± 21.5 | -46.1 ± 22.8 | -38.8 ± 19.7 | -39.0 ± 21.6 |
| | **Wet (-35 kPa)** | -35.9 ± 13.2 | -44.2 ± 6.8 | -39.1 ± 14.6 | -43.6 ± 12.1 | -40.5 ± 12.5 |
| | **Medium (-45 kPa)** | -46.7 ± 13.3 | -46.7 ± 9.9 | -50.4 ± 8.9 | -42.9 ± 4.9 | -47.0 ± 10.0 |
| | **Dry (-55 kPa)** | -41.4 ± 19.4 | -48.5 ± 10.5 | -46.9 ± 13.6 | -54.1 ± 8.0 | -48.0 ± 13.6 |
| **Number of irrigation⌠** | **Grower** | 23 | 22 | 20 | 13 | 19.5 |
| | **Wet** | 17 | 14 | 18 | 17 | 16.5 |
| | **Medium** | 14 | 15 | 16 | 12 | 14.25 |
| | **Dry** | 11 | 13 | 17 | 14 | 13.75 |

† The experiment was performed from April 3rd to August 19th 2012, April 2nd to August 15th 2013, April 1st to August 8th 2014 and May 18th to August 8th 2015.

‡ %ETc calculated as the sum of irrigation water use and rainfall divided by ETc calculated with Kc provided by Allen et al. (1998). Values in parentheses are in millimeters.

§ Average SWTT ± Standard deviation

⌠ Number of irrigation corresponds of the number of samples used for mean SWTTs

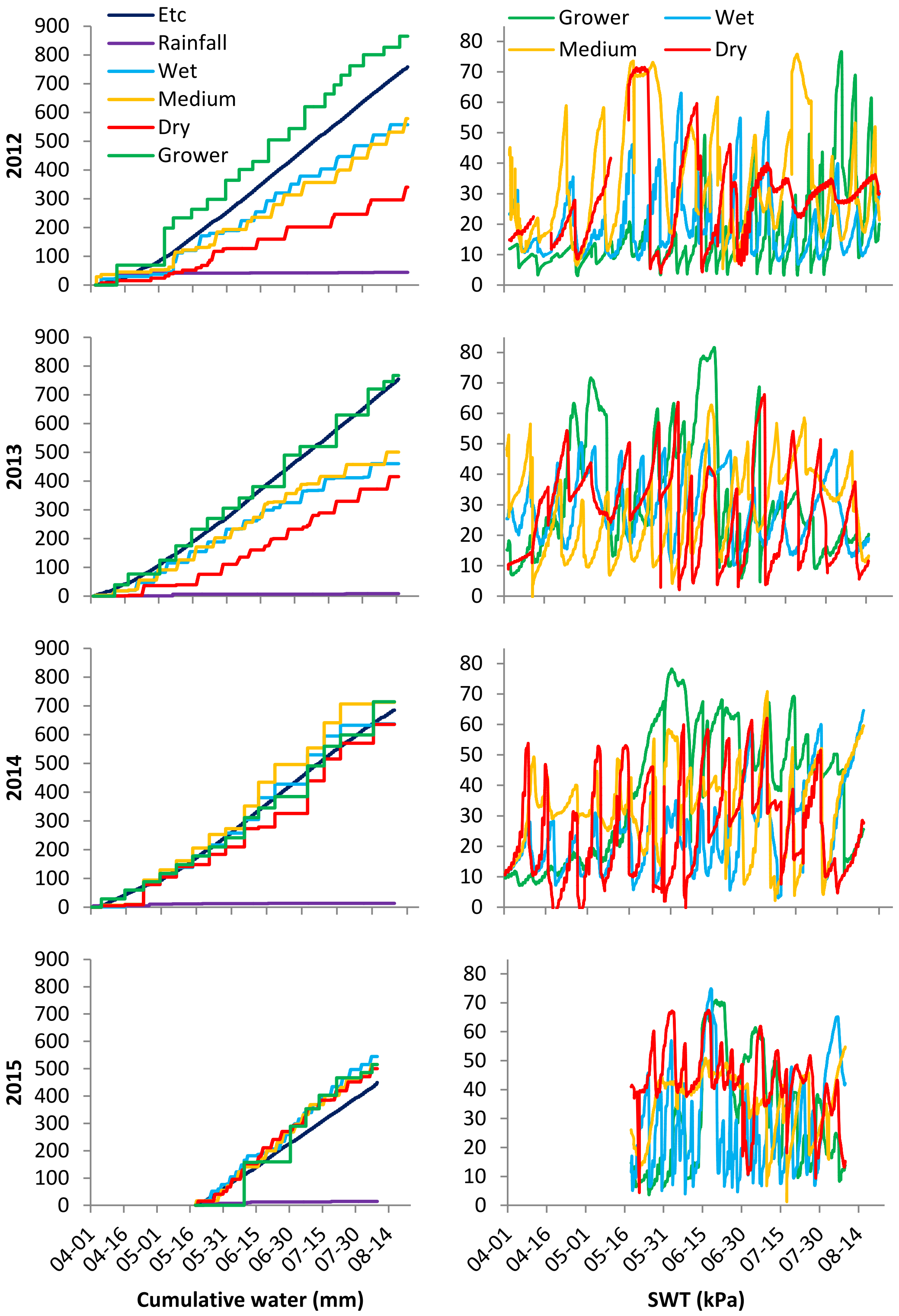


**Figure 2.3. Cumulative water (left) and mean SWT (right) of the 25 and 50 cm depth tensiometers in the treatments for 2012, 2013, 2014 and 2015.**

A water use evolution is observable through all years for SWTT treatments, but mainly for the dry treatment. Even if a same SWTT was targeted, water use in %ETc increased from 2012 to 2015. This increase was observed from 2013 for the wet and medium treatments. This progression was particularly obvious at the end of 2015. That year, all treatments used more water than ETc even if the tensiometers were working. This is explained by the fact that after a dry period, almond trees reacted by increasing root exploration in the wetted irrigation pattern. In 2015, more roots were observed with depth compared to 2012. This increased in root density caused a change in the wetting bulb dimension and then, a reduction of water around the tensiometers. As tensiometers remained at the same location from year to year, it resulted in a dryer interpretation of the readings and therefore, an increase in water application. This is consistent with Coelho and Or (1999) and Vrugt et al. (2001) who showed that irrigation strategy influences roots development.

Generally, targeted SWTT treatments slightly differed from observed values as thresholds were difficult to achieve at the beginning of the season during fertigation and were exceeded at the end during the drying period, due to delayed water applications associated with reduced water allocation and availability. Furthermore, as only one station of three tensiometers was used for each treatment, occasional technical issues (lack of communication between probes, probe damages, tensiometer refilling) may have sporadically caused a 24-hour irrigation delay communication problem. Also, as irrigation water had to be ordered for a specific threshold and that tension readings at 50 cm and 75 cm were affected only a couple of hours after the beginning of the irrigation, irrigation start needed to be approximated. In average, the water front reached the 25 cm, 50 cm and the 75 cm tensiometers respectively about 7.25 h, 13.5 h and 21 h after the beginning of the irrigation. That caused irrigation to start sometimes too early and sometimes too late relative to the targeted threshold. However, aside the wet treatment in 2013, thresholds for all treatments were not significantly different from targeted values. The most important difference between treatments was that the grower treatment used more water, but had a more variable threshold. This shows that grower irrigated sometimes when the soil was still wet enough and sometimes when it was too dry. That may have resulted in additional surface evaporation and percolation.

The consequence of algae clogging in the wet treatment can be observed in 2013 with the MSWP (Table 2.III). Increase in water use can also be observed with the MSWP in the dry treatment that increases in the same way from 2012 to 2015. However, globally, the MSWP and VPDleaf of the dry (-1.346 MPa, 2.419 kPa) treatment were significantly lower than the others. Wet (-1.246 MPa, 2.371 kPa) and medium (-1.198 MPa, 2.354 kPa) treatments were similar (except in 2013 for MSWP). Grower (-1.089 MPa, 2.297 kPa) treatment was the least stressed and this is consistent with a higher water consumption. Mean season MSWP of all treatments were generally maintained in the mild stress zone (-1.0 to -1.4 MPa) according to Fulton et al. (2014) except for the dry treatment in 2012-2013 (-1.643 and -1.401 MPa) and the wet treatment in 2013 (-1.520 MPa). This indicates the sensitivity of tension measurements in comparison to MSWP.

**Table 2.III : Midday stem water potential (MSWP) and leaf vapor pressure deficit (VPDleaf) for each year and irrigation treatment**

| | Treatment | 2012 | 2013 | 2014 | 2015 | Mean 2012-2015 |
|---|---|---|---|---|---|---|
| **MSWP (MPa)** | **Grower** | -0.945 a† | -1.049 a | -1.264 bc | -1.099 ab | -1.089 a |
| | **Wet** | -1.158 b | -1.520 d | -1.146 a | -1.163 b | -1.246 c |
| | **Medium** | -1.198 b | -1.226 b | -1.191 ab | -1.179 b | -1.198 b |
| | **Dry** | -1.643 c | -1.401 c | -1.333 d | -1.007 a | -1.346 d |
| | **LSD** | 0.066 | 0.095 | 0.077 | 0.101 | 0.041 |
| | **P** | <0.0001 | <0.0001 | 0.0005 | 0.0099 | <0.0001 |
| **VPDleaf (kPa)** | **Grower** | 2.536 a | 2.283 a | - - | 2.072 ns | 2.297 a |
| | **Wet** | 2.562 a | 2.431 bc | - - | 2.120 ns | 2.371 bc |
| | **Medium** | 2.585 a | 2.351 ab | - - | 2.125 ns | 2.354 b |
| | **Dry** | 2.715 b | 2.457 c | - - | 2.083 ns | 2.419 c |
| | **LSD** | 0.084 | 0.098 | - | 0.101 | 0.056 |
| | **P** | 0.0011 | 0.0050 | - | 0.6241 | 0.0009 |

† For each year, means followed by the same lowercase letter (a, b, c, d) across columns are not significantly different using least significant difference (LSD) at probability (P) ≤ 0.05. When "ns" follows the means, no significant differences were found between treatments.

### 2.2.2. Yield Measurements

Table 2.IV presents the mean marketable yield for each year of the experiment and for all treatments. The mean yield of the site was more (3114 kg/ha) than the average yield in California (2477 kg/ha) for the same period. From 2012 to 2014, mean yields of the site (2818, 3486 and 3811 kg/ha) tended to increase more than the average yield in California (2589, 2645 and 2410 kg/ha), but went down to the same level in 2015 (2343 compared to 2387 kg/ha) (CDFA, USDA, and NASS 2016).

**Table 2.IV : Almond yield for each year and irrigation treatment**

| | Treatment | 2012 | 2013 | 2014 | 2015 | Mean 2012-2015 |
|---|---|---|---|---|---|---|
| Yield (kg ha$^{-1}$) | Grower | 3194 a† | 4052 a | 3699 ns | 2183 b | 3280 a |
| | Wet | 2680 ab | 3134 c | 3913 ns | 2085 b | 2949 b |
| | Medium | 3067 a | 3599 b | 4110 ns | 2332 b | 3273 a |
| | Dry | 2330 b | 3160 c | 3525 ns | 2771 a | 2942 b |
| | LSD | 646 | 262 | 614 | 438 | 242 |
| | P | 0.0470 | <0.0001 | 0.2429 | 0.0211 | 0.0038 |

| | | 2012 | | 2013 | | 2014 | | 2015 | |
|---|---|---|---|---|---|---|---|---|---|
| | | P | R² | P | R² | P | R² | P | R² |
| Linear contrast‡ | SWTT | - | 0.0169 | - | 0.2299 | - | 0.0009 | - | 0.2151 |
| | MSWP | 0.0127 | 0.1999 | 0.0008 | 0.5568 | 0.4331 | 0.0704 | 0.1558 | 0.1997 |
| | VPDleaf | 0.0171 | 0.1797 | <0.0001 | 0.5679 | - | - | 0.3103 | 0.0386 |
| | % ETc | - | 0.1795 | - | 0.5219 | - | 0.0633 | - | 0.2154 |

† For each year, means followed by the same lowercase letter (a, b, c, d) across columns are not significantly different using least significant difference (LSD) at probability (P) ≤ 0.05. When "ns" follows the means, no significant differences were found between treatments.

‡ Linear contrast to determine the relationships between seasonal yield and the following variables: soil water tension threshold (SWTT), midday stem water potential (MSWP), leaf vapor pressure deficit (VPDleaf) and %ETc.

Except for 2015, average yield from the medium treatment was always higher than those from the wet and dry treatments. The results associated with the wet treatment could be explained by the increase of vegetative growth as it has been reported by other studies (Ebel, Proebsting, and Evans 1995; Hutmacher et al. 1994) or by the root asphyxia which caused stomatal closure and then photosynthesis decrease (Amador et al. 2012). Yield reduction in the dry treatment was related to a diminution of the fruit load and kernel size. For all four years, although the grower and medium treatments had the same average yield, the medium treatment used 557 mm less water. The grower treatment had better yield than the wet treatment even if it received more water. This may be explained by a more variable irrigation pattern. Dry periods in grower treatment may have allowed enough oxygen to enter in the soil profile in comparison to the more uniform irrigation pattern of the wet treatment.

There were significant yield differences between years ($P < 0.0001$), interactions of treatments and years ($P=0.0004$) and treatments and blocks ($P < 0.0001$). Although the correlations were generally low, there were significant linear relationships between MSWP/VPDleaf and yield in 2012 and 2013.

Figure 2.4 shows all the data for each year of MWSP (a), VPDleaf (b) and %ETc (c) related to yield. MSWP for grower treatment was concentrated in the -0.8 to -1.4 MPa range. The wet and the medium treatments were in the -1.0 to -1.4 MPa range except in 2013 for the wet treatment where MSWP was lower than -1.4 MPa. The dry treatment was generally lower than -1.3 MPa (indicating more stress) except in 2015 where MSWP was below -1.2 MPa. According to the boundary line, optimum yield related to MSWP were observed between -1.1 and -1.3 MPa. It is consistent with Fulton et al. (2014) who suggested maintaining MSWP in the -1.0 to -1.4 MPa range from mid-June to July. VPDleaf data were more spreaded out in the 2 to 2.9 kPa range. Better yields corresponded to VPDleaf between 2.2 and 2.5 kPa. Even if there were only one %ETc value for each treatment in each year, the boundary line indicated the highest yields near 100% ETc, using Kc recommended by Allen et al. (1998). In the same way, we can use the boundary line on SWTT and yield data to obtain the optimal value (Figure 2.5). This relationship has been extended using mean field yield data from other sites and other years. Using a polynomial regression on the boundary data, a SWTT of -45 kPa appears to be optimal. This is wetter than the recommendations of Taylor (1965) and Micke (1996) who suggested starting irrigation between -50 to -80 kPa for deciduous fruit trees or between -50 to -70 kPa at the depth of 45 to 60 cm for almonds. However, looking only at the results obtained in the experimental treatments (from 2012 to 2015) (Figure 2.5), it seems that a little deviation from the -45 kPa targeted value would decrease the marketable yield more importantly than the boundary line responses obtained with values from the neighboring fields from different years monitored with SWT stations.

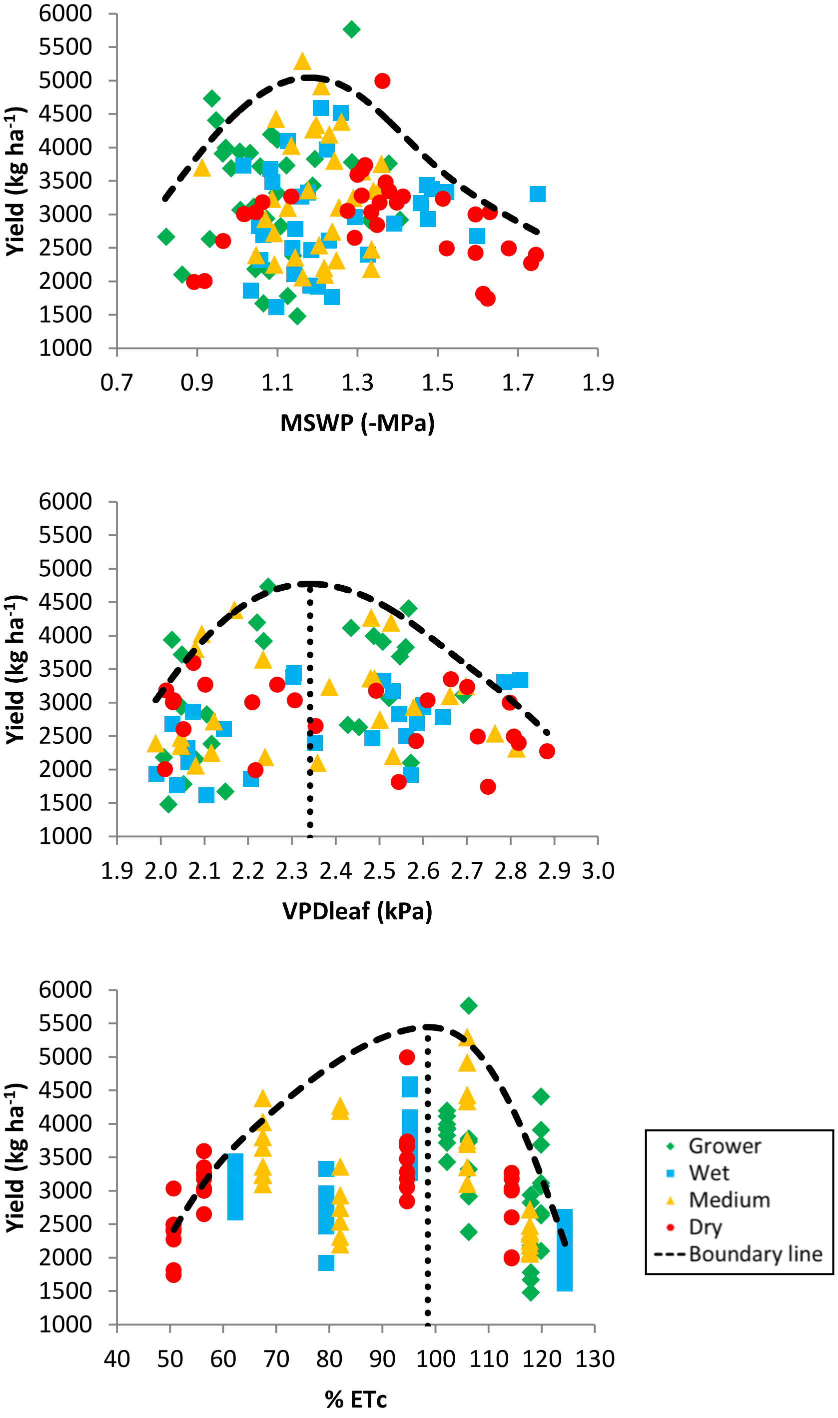


**Figure 2.4. MSWP, VPDleaf and %ETc related to yield for all years of experiments, except for VDPleaf in 2014 where leaves temperature were missing.**

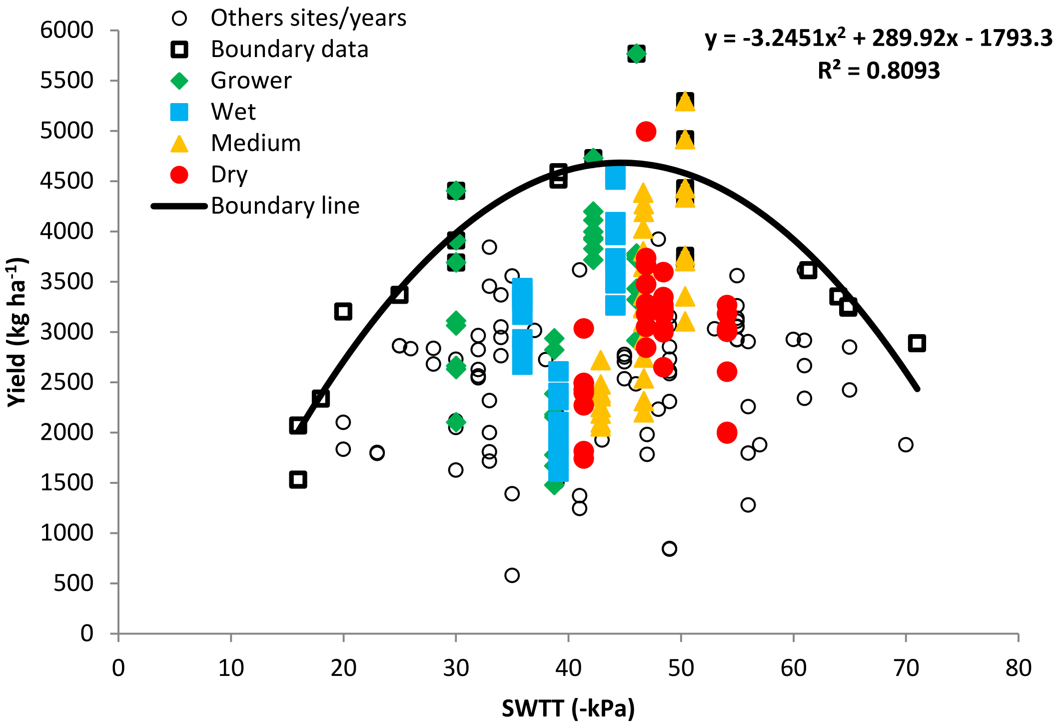


**Figure 2.5. SWTT and almond yield relationship with the boundary line approach.**

Figure 2.6 shows simulated relationships between MSWP and SWTT with %ETc using boundary lines of yield. Even if the intervals between our SWTT were relatively large, our treatments were still in the mild stress range according to MSWP. This indicates the greater sensitivity of the tensiometers. According to these parameters, boundary lines show that almond yield seems to be affected by irrigation deficit as well as irrigation excess. Most studies are principally on deficit irrigation, so little information is available on the effects of water excess in almond production. In a young orchard, Hutmacher et al. (1994) found no significant difference in yield for treatment having 150 and 175% ETc using drip irrigation. However, their experience showed leaching even at the rate of 100% ETc and the authors questioned their irrigation frequency, application rates and wetted volume. They also noticed that applying more water than full-water requirements increased vegetative growth. On the other hand, Girona et al. (2005) reported no extra vegetative growth for 130% ETc treatment and a non-significant decrease in yield between 70 and 130% relative to a 100% ETc in a young orchard under micro-sprinkler irrigation. Nevertheless, even if this phenomenon is more frequent in flood irrigation, it is also known that hypoxia caused atmospheric gases exchange problems and then growth diminution (Drew 1983).

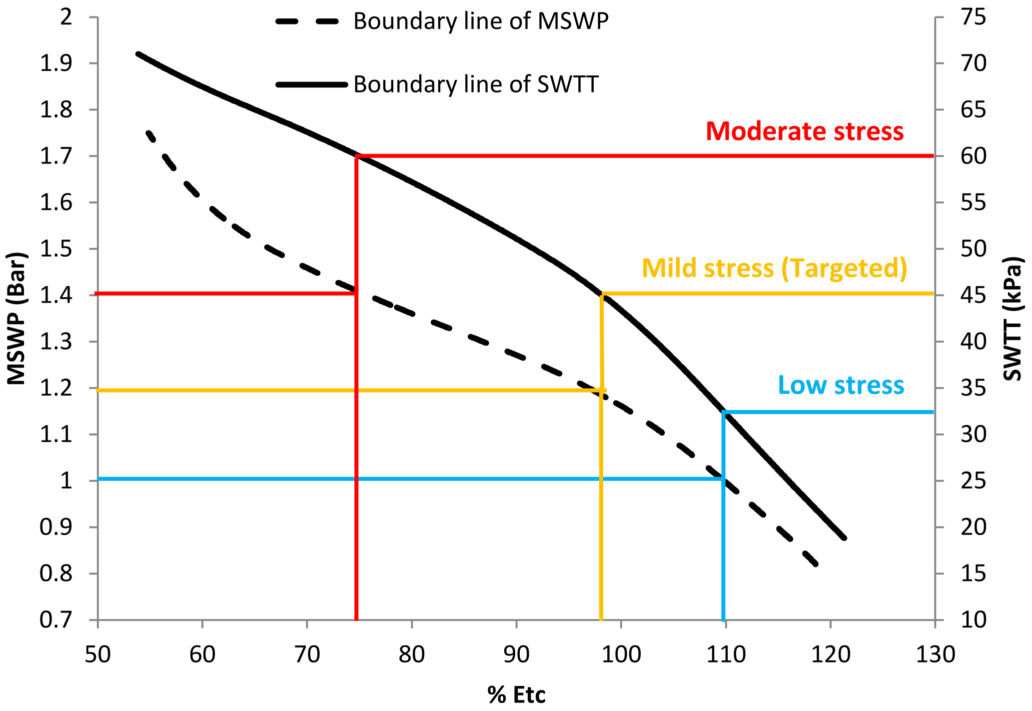


**Figure 2.6. Reported boundary %ETc and MSWP/SWTT values relationship using yield boundary data. Red, orange and blue lines represent crop stress associated with different MSWP levels in almonds according to Fulton et al. (2014).**

Importantly, in our case, using Kc recommended by Goldhamer (Steduto et al. 2012) as well as Sanden (Sanden 2009) would have resulted in almost 20% ETc more water consumption in comparison to those suggested by Allen et al. (1998), Girona (2006) and Goldhamer and Viveros (2000) (Figure 2.7) if the producer would have used them to achieve the 100% ETc water requirements. According to our results, it would probably have caused yield diminution and overuse of water. This emphasizes the importance of Kc in irrigation scheduling using ETc.

Further researches are needed to determine SWTT depending on the stage of growth and to adjust the latter according to spatiotemporal variability.

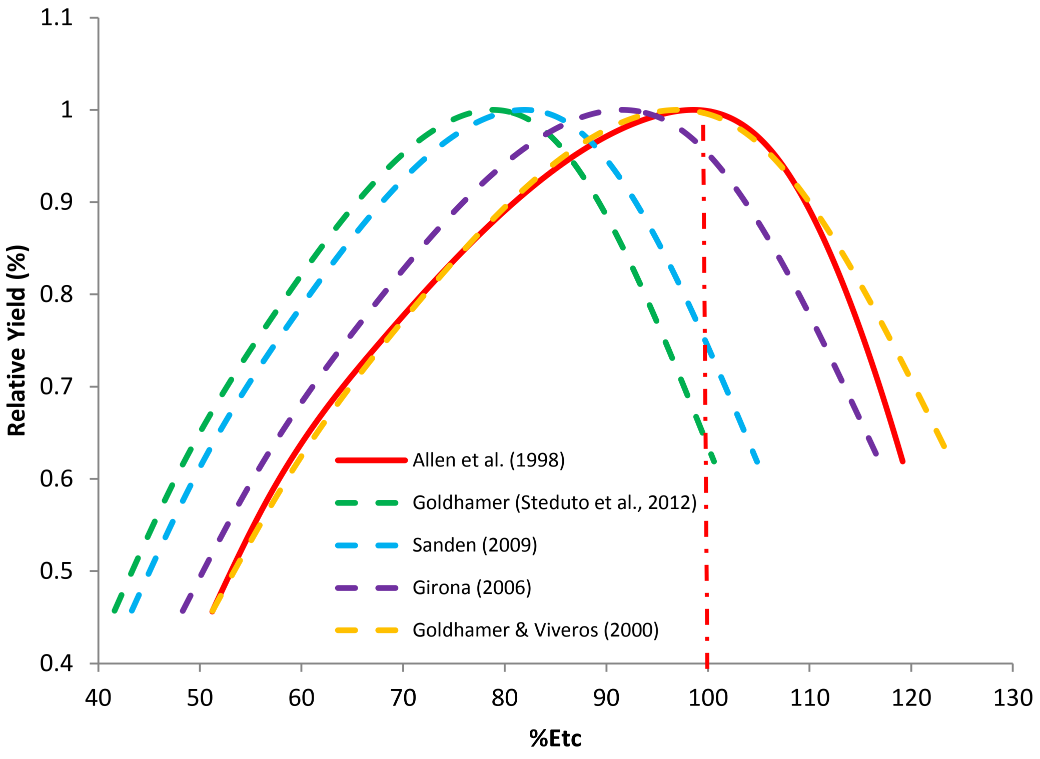


**Figure 2.7. %ETc related to yield for all years of the experiment, using Kc from Allen et al. (1998), Goldhamer (Steduto et al., 2012), Sanden (2009), Girona (2006) and Goldhamer & Viveros (2000).**

### 2.2.3. Practical implications

Firstly, the results of this study illustrate that growers under the same orchard conditions can use a SWTT of -45 kPa between May to harvest for irrigation scheduling using tensiometers. This threshold represents the mean value between tensiometers placed at the depth of 25 and 50-cm. Irrigation should be stopped when the wetting front reached the 75-cm tensiometer. Tensiometers should be placed in the wet zone and moved as the irrigation strategy influences the roots development. Hence, it is recommended to move them towards the irrigation line the first years they are used to ensure good readings until equilibrium occurs between water and nutrient requirements in root exploration. Frequent and sustained maintenance is recommended then. If only one tensiometer station is used in a field, it should be coupled with direct observations or plant measurements of MSWP several times during the season to ensure good performance of the system. Secondly, this study shows that almond yield is affected by excess water which could be explained by an extra-vegetative growth or by root asphyxia. Thirdly, we found that new Kc recommended for almond production used in our conditions would have increased water use and even decreased marketable yield. Growers should be careful and use Kc according to their orchard characteristics.

## 2.3. Conclusion

The medium treatment allowed water savings of about 20% in comparison to the grower treatment without decreasing average yield for the four years of the experiment. A SWTT of -45 kPa should be used in sandy loam under San Joaquin Valley conditions between May to harvest. It would result in a reduction of irrigation water use without affecting productivity. This study also showed that almond trees are negatively affected by both an excess irrigation regime and by deficit irrigation. Finally, some attention should be paid to crop coefficient recommendations in almond orchards to ensure optimal yield and water use.

## 2.4. Acknowledgements

The authors thank Natural Science and Engineering Research Council of Canada (NSERC) and Le Fonds de Recherche Nature et Technologies du Québec for their financial contributions. We also acknowledge Hortau Inc. for the financial and technical support, and all undergraduates, graduates and professional who helped in this study.

## 2.5. References

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith. 1998. “Crop Evapotranspiration: Guidelines for Computing Crop Requirements.” *Irrigation and Drainage Paper No. 56, FAO* (56):300.

Almond Board of California. 2015. “Almonds and Water 101.”

Almond Board of California. 2016. “California Almond Industry Facts.”

Amador, M. L., S. Sancho, B. Bielsa, J. Gomez-Aparisi, and M. J. Rubio-Cabetas. 2012. “Physiological and Biochemical Parameters Controlling Waterlogging Stress Tolerance in Prunus before and after Drainage.” *Physiologia Plantarum* 144(4):357–68.

Andreu, L., J. W. Hopmans, and L. J. Schwankl. 1997. “Spatial and Temporal Distribution of Soil Water Balance for a Drip-Irrigated Almond Tree.” *Agricultural Water Management* 35(1–2):123–46.

Bernstein, L., J. W. Brown, and H. E. Hayward. 1956. “The Influence of Rootstock on Growth and Salt Accumulation in Stone-Fruit Trees and Almonds.” *Proc. Am. Soc. Hort. Sci.* (68):86–95.

Brown, J. R. 1988. “Recommended Chemical Soil Test Procedures for the North Central Region.” *North Central Regional Research Publication* 221(221):1–71.

Brown, J. W., C. H. Wadleigh, and H. E. Hayward. 1953. “Foliar Analysis of Stone Fruit and Almond Trees on Saline Substrates.” *Proc. Am. Soc. Hort. Sci.* (61):49–55.

California Department of Water Resources. 2014. “Water Year 2014 Ends as 3rd Driest in Precipitation.”

Canessa, P., S. Green, and D. Zoldoske. 2012. “Agricultural Water Use in California: A 2011 Update.” *The Center for Irrigation Technology* (289).

CDFA, USDA, and NASS. 2016. *2016 California Almond Nursery Sales Report*.

Coelho, E. F. and D. Or. 1999. “Root Distribution and Water Uptake Patterns of Corn under Surface and Subsurface Drip Irrigation.” *Plant and Soil* 206(2):123–36.

Croyle, W. A., J. Jones, B. Nozuka, and M. Alemi. 2014. *Public Update for Drought Response*.

Dane, J. H. and J. W. Hopmans. 2002. “Pressure Cell.” Pp. 684–92 in *Methods of Soil Analysis. Part 4-Physical Methods*. Soil Science Society of America Book series.

Dhillon, R., V. Udompetaikul, F. Rojo, and J. Roach. 2014. “Detection of Plant Water Stress Using Leaf Temperature and Microclimatic Measurements in Almond, Walnut, and Grape Crops.” *Transactions of the ASABE* 57(1):297–304.

Drew, M. C. 1983. “Plant Injury and Adaptation to Oxygen Deficiency in the Root Environment: A Review.” *Plant and Soil* 75(2):179–99.

Ebel, R. C., E. L. Proebsting, and R. G. Evans. 1995. “Deficit Irrigation to Control Vegetative Growth in Apple and Monitoring Fruit Growth to Schedule Irrigation.” *HortScience* 30(6):1229–32.

Fereres, E. 1996. “Irrigation Scheduling of Horticultural Crops.” *II International Symposium on Irrigation of Horticultural Crops* 449:253–58.

Fereres, E. and D. A. Goldhamer. 2003. “Suitability of Stem Diameter Variations and Water Potential as Indicators for Irrigation Scheduling of Almond Trees.” *Journal of Horticultural Science and Biotechnology* 78(2):139–44.

Fulton, A., R. Buchner, B. Olson, L. Schwankl, C. Gilles, N. Bertagna, J. Walton, K. Shackel.2001. “Rapid Equilibration of Leaf and Stem Water Potential under Field Conditions in Almonds, Walnuts, and Prunes.” *HortTechnology* 11(4):609–15.

Fulton, A., J. Grant, R. Buchner, and J. Connell. 2014. “Using the Pressure Chamber for Irrigation Management in Walnut, Almond, and Prune.” *ANR Publication 8503* 1–27.

Girona, J. 2006. “La Respuesta Del Cultivo Del Almendro Al Riego.” *Vida Rural* (Septiembre):12–16.

Girona, J., M. Mata, and J. Marsal. 2005. “Regulated Deficit Irrigation during the Kernel-Filling Period and Optimal Irrigation Rates in Almond.” *Agricultural Water Management* 75(2):152–67.

Goldhamer, D. A. and M. Viveros. 2000. “Effects of Preharvest Irrigation Cutoff Durations and Postharvest Water Deprivation on Almond Tree Performance.” *Irrigation Science* 19(3):125–31.

Goldhamer, D. A., M. Viveros, and M. Salinas. 2006. “Regulated Deficit Irrigation in Almonds: Effects of Variations in Applied Water and Stress Timing on Yield and Yield Components.” *Irrigation Science* 24:101–14.

Hodnett, M. G., J. P. Bell, P. D. Ah Koon, G. C. Soopramanien, and C. H. Batchelor. 1990. “The Control of Drip Irrigation of Sugarcane Using ‘index’ Tensiometers: Some Comparisons with Control by the Water Budget Method.” *Agricultural Water Management* 17(1–3):189–207.

Hutmacher, R. B. et al. 1994. “Growth and Yield Responses of Almond (Prunus-Amygdalus) To Trickle Irrigation.” *Irrigation Science* 14:117–126 ST–GROWTH AND YIELD RESPONSES OF ALMOND.

Jones, H. G. 2004. “Irrigation Scheduling: Advantages and Pitfalls of Plant-Based Methods.” *Journal of Experimental Botany* 55(407):2427–36.

Koumanov, K. S., J. W. Hopmans, L. J. Schwankl, L. Andreu, and A. Tuli. 1997. “Application Efficiency of Micro-Sprinkler Irrigation of Almond Trees.” *Agricultural Water Management* 34(3):247–63.

Koumanov, K. S., J. W. Hopmans, and L. W. Schwankl. 2006. “Spatial and Temporal Distribution of Root Water Uptake of an Almond Tree under Microsprinkler Irrigation.” *Irrigation Science* 24(4):267–78.

Létourneau, G., J. Caron, L. Anderson, and J. Cormier. 2015. “Matric Potential-Based Irrigation Management of Field-Grown Strawberry: Effects on Yield and Water Use Efficiency.” *Agricultural Water Management* 161:102–13.

Maas, E. V. 1990. “Crop Salt Tolerance.” *Agricultural Salinity Assessment and Management* American S(71).

Maes, W. H. and K. Steppe. 2012. “Estimating Evapotranspiration and Drought Stress with Ground-Based Thermal Remote Sensing in Agriculture: A Review.” *Journal of Experimental Botany* 63(13):4671–4712.

Micke, W. C. 1996. *Almond Production Manual*. UCANR Publications.

Micke, W. C. and D. E. Kester. 1998. “Almond Growing in California.” *Acta Horticultura* (470):21–28.

Moutonnet, P., M. Brandy-Cherrier, and J. Chambon. 1981. “Possibilités d’Utilisation Des Tensiomètres Pour l’Automation de l’Irrigation.” *Plant and Soil* 59:335–45.

Naor, A. 2006. “Irrigation Scheduling and Evaluation of Tree Water Status in Deciduosus Orchads.pdf.” 32:111–65.

O’Green, T., J. Deng, P. Hartsough, and S. Wilson. 2016. “California Soil Survey.”

Pelletier, V., J. Gallichand, and J. Caron. 2013. “Effect of Soil Water Potential Threshold for Irrigation on Cranberry Yield and Water Productivity.” *Transactions of the American Society of Agricultural and Biological Engineers* 56(6):1325–32.

Périard, ., J. Caron, J. Lafond, and S. Jutras. 2015. “Root Water Uptake by Romaine

Lettuce in a Muck Soil : Linking Tip Burn to Hydric Deficit.” *Vadose Zone Journal* 14(6):13.

Rekika, D. et al. 2014. “Optimal Irrigation for Onion and Celery Production and Spinach Seed Germination in Histosols.” *Agronomy Journal* 106(3):981.

Reynolds, W. D. 2008. “Saturated Hydraulic Properties : Laboratory Methods.” Pp. 1013–24 in *Soil Sampling and Methods of Analysis*, edited by C. M.R. and E. G. Gregorich. Canadian Society of Soil Science, CRC Press.

Richards, S. J. and A. W. Marsh. 1961. “Irrigation Based on Soil Suction Measurements.” *Soil Science Society of America Proceedings* 25(1):65–69.

Sanden, B. 2009. “Managing Mid-Season Almond Irrigation , Hull Rot & Regulated Deficit Irrigation.” 1–5.

Schnug, E., J. Heym, and F. Achwan. 1996. “Establishing Critical Values for Soil and Plant Analysis by Means of the Boundary Line Development System (Bolides).” *Communications in Soil Science and Plant Analysis* 27(13–14):2739–48.

Shackel, K. A. et al. 1997. “Plant Water Status as an Index of Irrigation Need in Deciduous Fruit Trees.” *HortTechnology* 7(1):23–29.

Shackel, K. A. 2007. “Water Relations of Woody Perennial Plant Species.” *Journal International des Sciences de la Vigne et du Vin* 41(3):121–29.

Steduto, P., T. C. Hsiao, E. Fereres, and D. Raes. 2012. “Crop Yield Response to Water.” *FAO Irrigation and Drainage Paper* (66):505.

Sumner, D. A., W. A. Matthews, J. Medellín-azuara, and A. Bradley. 2014. “The Economic Impacts of the California Almond Industry.” 53.

Taylor, S. A. 1965. “Managing Irrigation Water on the Farm.” *Transactions of the ASAE* 8(3):433–36.

Torrecillas, A., J. J. Alarcón, R. Domingo, J. Planes, and M. J. Sánchez-Blanco.

1996. “Strategies for Drought Resistance in Leaves of Two Almond Cultivars.” *Plant Science* 118(2):135–43.

USDA/NASS. 2015. *Agricultural Statistics 2015*.

Vrugt, JA, JW Hopmans, and Jirka Simunek. 2001. “Calibration of a Two-Dimensional Root Water Uptake Model.” *Soil Science Society of America Journal* 65(4):1027–37.

Webb R.A. 1972. “Use of Boundary Line in the Analysis of Biological Data.” *Journal of horticultural Science* 47:309–19.

Williams, L. E. and F. J. Araujo. 2002. “Correlations among Predawn Leaf, Midday Leaf, and Midday Stem Water Potential and Their Correlations with Other Measures of Soil and Plant Water Status in Vitis Vinifera.” *J. Amer. Soc. Hort. Sci.* 127(3):448–54.

# Chapitre 3 : Performance evaluation of soil water tension for managing irrigation at different spatial scale – Case study of an almond orchard in California – Évaluation de la performance d’une stratégie d’irrigation par tensiométrie à différentes échelles spatiale – Étude d’un site de production d’amandes en Californie

Auteurs : Gabriel Collin, Jean Caron, Jacques Gallichand

# Résumé

Les impacts de la variabilité spatio-temporelle du potentiel matriciel de l'eau du sol ainsi que les aspects économiques qui y sont liés ont été déterminés pour permettre d'ajuster la recommandation d'un seuil d'irrigation pour la production d'amandes. L'étude a été effectuée avec l'aide de 27 stations de 2 tensiomètres à 25 et 50 cm de profondeur positionnés en quinconce sur l'ensemble d'un champ de 75 acres. Les stations ont été installées dans les amandiers de la variété Nonpareil du 28 juin au 22 juillet 2015. Durant cette période, un total de 10 irrigations sont survenues. Les irrigations étaient entièrement contrôlées par le producteur. Les résultats montrent que le patron spatial de la tension est stable pendant environ 1 mois et demi. C'est-à-dire que sur l'ensemble des mesures, l'ordre de celles-ci (du plus sèche au plus humide) reste le même durant cette période. Les mesures de tension ne sont pas ou très peu corrélées dans l'espace, et sont plutôt distribuées aléatoirement de façon lognormale entre les périodes d'irrigation. Les distributions empiriques ayant les mêmes moyennes de tensions restent significativement semblables durant les périodes d'assèchement, et ce, pour l'ensemble de la durée de l'expérience. L'étendue de la variance des mesures de tension augmente quant à elle dans le même sens que la moyenne. Donc, plus le sol s'assèche, plus l'écart entre les tensions augmente.

Avec la méthode proposée dans cette étude, considérant différents critères économiques ainsi que la variabilité des mesures de la tension, les producteurs d'amandes ne voulant pas modifier leurs zones d'irrigation seraient avantagés d'utiliser 5 stations pour des champ de 30 ha (75 acres). Ceux-ci devraient s'assurer que la moyenne des tensions moyennes à 25 et 50 cm de ces 5 stations ne dépasse pas -45 kPa.

Mots clés: Amandes, irrigation, potentiel matriciel, fonction d'autocorrélation, test de Spearman, géostatistique, fonction de densité de probabilité, simulation de Monte Carlo.

# Abstract

The impacts of the spatial and temporal variability of soil water tension (SWT) for managing irrigation of almond production was assessed. The study was carried out with 27 stations of 2 tensiometers at depths of 25 and 50 cm grouped in quincunx over a 30-ha (75-acre) field. Stations were distributed among Nonpareil almond trees from June 28 to July 22 2015, corresponding to 10 irrigation events. Irrigation was entirely controlled by the producer. The results show that the spatial pattern of SWTs was stable for about a month and a half. That is to say that on the whole measurements, the order of these (from the driest to the wettest) remains the same during this period. Tension measurements were either slightly spatially correlated or uncorrelated, and were log-normally distributed between periods of irrigation. The empirical probability distributions with the same mean tensions remained significantly similar during the drying periods for the entire duration of the experiment. Furthermore, the variation of tension measurements tended to increase with the mean value. So, as the soil dries up, the gap between tensions increased.

Taking into account various economic criteria as well as the variability of the SWT measurements, almond producers should use 5 stations per field of 30-ha (75-acre) field. These should ensure that the average of the mean tension at 25 and 50 cm of these 5 stations do not exceed -45 kPa.

Keywords: Almonds, irrigation, soil water matric potential, autocorrelation function, Spearman test, geostatistics, probability density function, Monte Carlo simulations.

# Introduction

Almonds [*Prunus dulcis* (Mill.) D.A. Webb] are considered a high-value tree crop which is principally grown in the Central Valley of California (Almond Board of California 2016; USDA/NASS 2015). With the persistent drought of the last years in this region (California Department of Water Resources 2014), producers and researchers have worked towards to optimize crop water use by adjusting the irrigated area, the period and the rate of water applications. Micro-irrigation allowed decreasing water use by about 33% (Almond Board of California 2015) in the last decade and different new methods for scheduling have been developed. These methods are based either on climatic, plant or soil measurements. The California irrigation management information system (CIMIS) is an example of a tool that growers can use to estimate crop evapotranspiration (Snyder et al. 1987). However, this method requires adapted crop coefficients which are variable from one site to another (Allen et al. 1998). Collin et al. (2017) showed that a difference in the choice of crop coefficients could increase by up to 20% water use and decrease marketable yields for a mature almond orchard. For almond production, some researchers have developed different plant methods based on midday stem water potential (MSWP) (Fulton et al. 2001, 2014; Shackel et al. 1997), sap flow (Fuentes et al. 2013; Romero, Muriel, and Garcia 2009), canopy temperature (Dhillon et al. 2014; Maes and Steppe 2012) and trunk diameter variations (Fereres and Goldhamer 2003). These methods are either difficult to automate (Jones 2004), need qualified operators (Williams and Araujo 2002) conducting many measurements (Fulton et al. 2001), or need developments before commercial use (Nortes et al. 2009). Using continuous soil water tension measurements, Collin et al. (2017) defined a soil water tension threshold of -45 kPa for mature Nonpareil almond trees using the mean values of tensiometers at depths of 25 and 50 cm. The research of Collin et al. (2017) determined that almond yield followed a polynomial regression to soil water tension threshold (SWTT). However, neither the spatiotemporal variability of SWT was accounted for in their recommendations nor was the economic effect related to the use of tensiometers for irrigation triggering. Measurements variability and cost are both important constraints limiting growers to use SWT for triggering irrigation

(Fereres 1996; Naor 2006). Therefore, the goal of this study was to adjust the SWTT recommendation according to both the spatiotemporal variability of SWT and a few economic parameters.

## 3.1. Materials and methods

### 3.1.1. Experimental Site

The experiment was conducted in 2015 in a mature almond orchard (*Prunus dulcis* (Mill.) D.A. Webb) located in Shafter, California (United States) (354,346° N, 119.2067 ° W) just outside Bakersfield in the San Joaquin Valley. The experiment was performed from June 28th to July 22nd (including 10 irrigation events) on a Milham sandy loam soil (O'Green et al. 2016) with the Nonpareil variety. The plot was installed in a 30-ha field with a tree spacing of 5.5 m × 7.3 m. Trees were irrigated by 12-jets micro-sprinklers (58 L/h @ 0.17–0.24 MPa (Gironet$^{TM}$, Netafilm, CA, USA)) placed midway between trees in the tree row with a wetted radius of approximately 2 m. The soil surface was free of weeds during the experiment and the irrigation was started according to grower management.

### 3.1.2. Experimental Design

The experimental plots were placed using a uniform design. The experiments included 27 wireless stations (TX3 wireless station, Hortau Inc., Québec, Canada) with two tensiometers located at depths of 25 and 50 cm. Tensiometers were placed in the wetted radius of the micro-sprinklers at a distance of approximately 0.5 m from the irrigation line. More information about the positioning of the tensiometers is presented by Collin et al. (2017). One of the stations had a pressure switch to determine the irrigation triggering. Soil water tension (SWT) and switch data were sent to a web server every 15 minutes and were readily accessible (Irrolis, www.hortau.com, Hortau Inc., Québec, Canada). Mean SWT at depths of the 25 and 50 cm were used to evaluate water stress. Two groups of three stations were placed closer to each other to evaluate short-distance spatial correlation. One group was placed on the same tree row between 4 trees (5.5 m) and the other group was placed perpendicularly to tree rows with one station in each nearest row of Nonpareil almond trees (14.6 m) (alternation of a different variety between Nonpareil rows). Figure 3.1 presents the experimental design with stations, laterals and main line location.

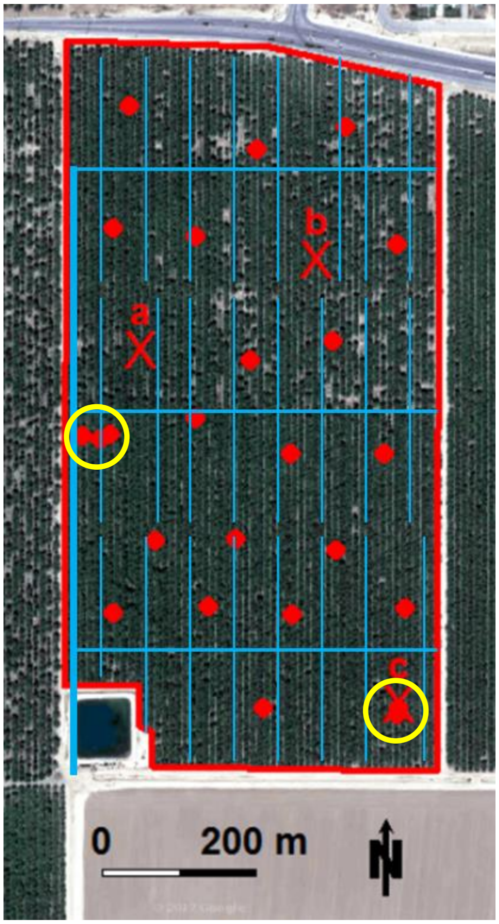


**Figure 3.1. Experimental design. Blue lines represent direction of the main line and the laterals. The three «Xs» represent the locations of the contrasting samples (a, b and c) represented in figure 8. Yellow circles represent the two groups of three stations used to evaluate low distance spatial correlation.**

### 3.1.3. Soil Properties

At each station location, two undisturbed soil samples (8.2 cm diameter and 5.5 cm length cores) were taken to determine saturated hydraulic conductivity, soil water retention curve (WRC), unsaturated hydraulic conductivity curves, particle size distribution and soil bulk density. The samples were taken at the same depth as the tensiometers at 25 cm and 50 cm The vertical constant head soil core method

(Reynolds 2008) was used to estimate saturated hydraulic conductivity and the multistep outflow method (Dane and Hopmans 2002) with a tension table (Soil Moisture Equipment Corp., USA) was used to measure WRC. Fixed points were obtained with a pressure plate apparatus at pressure set at 33, 100 and 1500 kPa were combined with tension table measurements. Tensions of 33 and 100 kPa were measured on each sample while only 10 samples were used at 1500 kPa because of time constraints. These ten samples were chosen considering the location and the depth (5 times at 25 cm, and 5 times at 50 cm) to be representative of the whole field. Parameters of the water desorption and the unsaturated hydraulic conductivity curve were fitted with HYDRUS-1D (PC-Progress) using data from both methods. Textural classification was measured with the sedimentation method and sand fraction was obtained at the end by sieving the sand samples (Centre d'expertise en analyse environnementale du Québec 2015).

### 3.1.4. Temporal Stability

To statistically test temporal stability of SWT spatial pattern, the nonparametric Spearman rank correlation test was used (Hendrickx and Wierenga 1990; Van Pelt and Wierenga 2001; Rolston, Biggar, and Nightingale 1991). Spearman coefficients ($\rho$) were calculated by

$$\rho = 1 - \frac{6\sum_{i=1}^{n}\left(R_{i,j} - R_{i,j'}\right)^2}{n(n^2-1)}$$

[Éq. 3.1]

Where $n$ is the number of stations (27), $R_{i,j}$ is the rank at the station $i$ at time $j$ and $R_{i,j'}$ at the same station but at another time *j'*. At the 5% level of a two-tailed test, $\rho$ values above 0.3822 were significant and indicated temporal persistence (Conover 1980). This means that the driest station at time $j$ stayed the driest at time *j'*. The autocorrelation function was also used to determine temporal stability of each station. The autocorrelation coefficient can be approximated (Wilks 2006) as:

$$r_{acf} = \frac{\sum_{i=1}^{N-j}(Y_i - \bar{Y})(Y_{i+j} - \bar{Y})}{\sum_{i=1}^{N}(Y_i - \bar{Y})^2}$$

[Éq. 3.2]

where $N$ is the number of measurements, $Y_i$ is the measurement at time $i$, $Y_{i+j}$ is the measurements at time $i+j$, $\bar{Y}$ is the mean value. The spearman rank correlation and the autocorrelation function were performed using “pspearman” (Savicky, P., 2014) and “stats” (The R Development Core Team, 2008) packages of the R software (The R Development Core Team, 2008).

### 3.1.5. Spatial Variability

Geostatistics were used to analyze the spatial structure of soil properties and SWT. Variographic analyzes combined with ordinary kriging (OK) as well as inverse distance weighting (with different weighting power parameters (p = 0.5, 1 and 2)) (IDW) and thin plate spline (TPS) were tested to determine the best interpolation method. Cross-validations were made based on different criteria such as mean error (ME), root mean square errors (RMSE), slope, intercept and $R^2$ according to observed and predicted values. For SWT, where measurements were not spatially structured according to the cross-validation criteria, frequency distributions were used instead. Kolmogorov-Smirnov (KS) test was chosen to compare empirical distributions to theoretical normal and log-normal distributions and pairs of empirical distributions (Conover 1980). The OK, IDW, and TPS were performed using the “automap”, “fields” and “gstat” packages (Hiemstra 2015; Nychka et al. 2016; Pebesma and Graeler 2015), the distribution adjustments with “fitdistrplus” (Delignette-Muller et al. 2016) and the KS test with “stats” (The R Development Core Team, 2008) of the R software (The R Development Core Team, 2008).

### 3.1.6. Economic Analysis

Additional net margin simulations using different economic parameters were made to observe the influence of their variation on irrigation recommendations. This partial economic analysis was based on several assumptions. Almond price was based on the 2012 to 2015 historical mean value (6.96 \$/kg) (CDFA, USDA, and NASS 2016), water cost was estimated at 0.559 \$/m³ including direct water price (0.527 \$/m³) (Howitt, Medellín-azuara, and Macewan 2015) and pumping cost (0.032 \$/m³) (Connell et al. 2012), and tensiometers stations price were variable and estimated between 4500\$ to 5500\$ per station per year according to the number of stations installed (Hortau Inc., Québec, Canada). It corresponds to a rental fee including up-to-date equipment and tight maintenance. Then, additional net margins corresponded to the gain in net profits obtained by additional yield multiplied by the almond price minus the difference in water use and minus the rental fee of the stations.

Using Monte Carlo simulations (Metropolis and Ulam 1949), we tested different scenarios with known SWT distributions. One, 2, …, 10 000 replicates of N= 1, 2, …, 27 SWT location measurements were generated according to the chosen SWT distributions. For each replicate, mean SWT measurements were calculated. So, based on the polynomial responses of almond yield to soil water tension threshold (SWTT) (Collin et al. 2017), yield was determined for each mean SWT measurements. Water consumption was estimated using linear regression presented by Collin et al. (2017). This model drew linear relationship between %ETc and SWTT. Millimeters of water as a function of % $ET_C$ was made according to historical ETc of the last five years from the beginning of May to mid-August (approximated harvest time for Nonpareil variety). Knowing the average yield, the average water consumption and the number of stations, we calculated the cost and the revenues, and then, the additional net margin.

## 3.2. Results and discussion

### 3.2.1. Soil properties variability

Soil textures vary from loamy sand to loam at 25 cm, and from loamy sand to clay loam at 50 cm. However, overall field soil texture is mostly a fine sandy loam at both 25 and 50 cm which is consistent with O'Green et al. (2016). Figure 3.2 presents contrasting differences in soil textures in the experimental setup with extremes and medium measured WRC and $K_{unsat}$ curves at 25 and 50 cm.

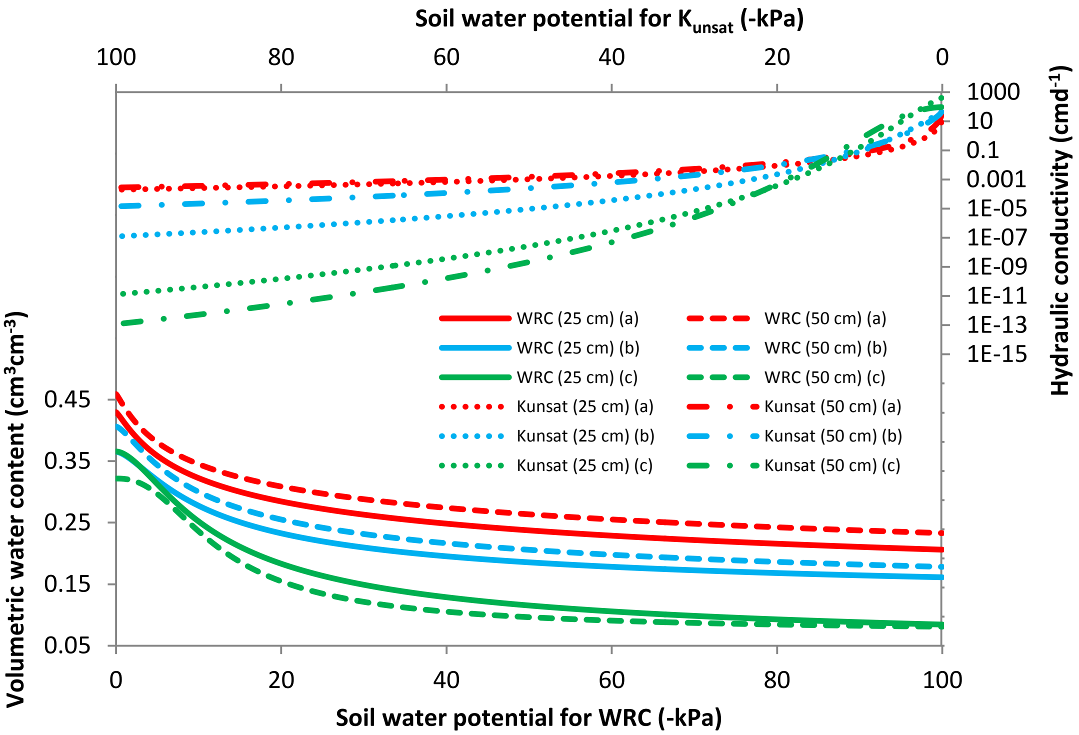


**Figure 3.2. Fitted volumetric water content and unsaturated hydraulic conductivity related to soil water potential of soil samples characteristics of three different zones (a, b and c) (shown on Figure 3.1) with contrasting differences in soil textures in the experimental setup.**

Using mean value at 25 and 50 cm and OK method, geostatistical analysis shows that texture presented left to right gradient, parallel to the irrigation lines (Figure 3.3). OK was chosen according to overall goodness of fit criteria even if TPS also showed relatively good results. Spatial interpolation method is soil-property dependent and gave good results only with sand and clay content, and available water content (AWC) (Table 3.I). Correlations between observed and predicted values for other properties like soil bulk density and saturated hydraulic conductivity were very low (not shown) which were probably caused by the small number of samples taken in the analyzed area.

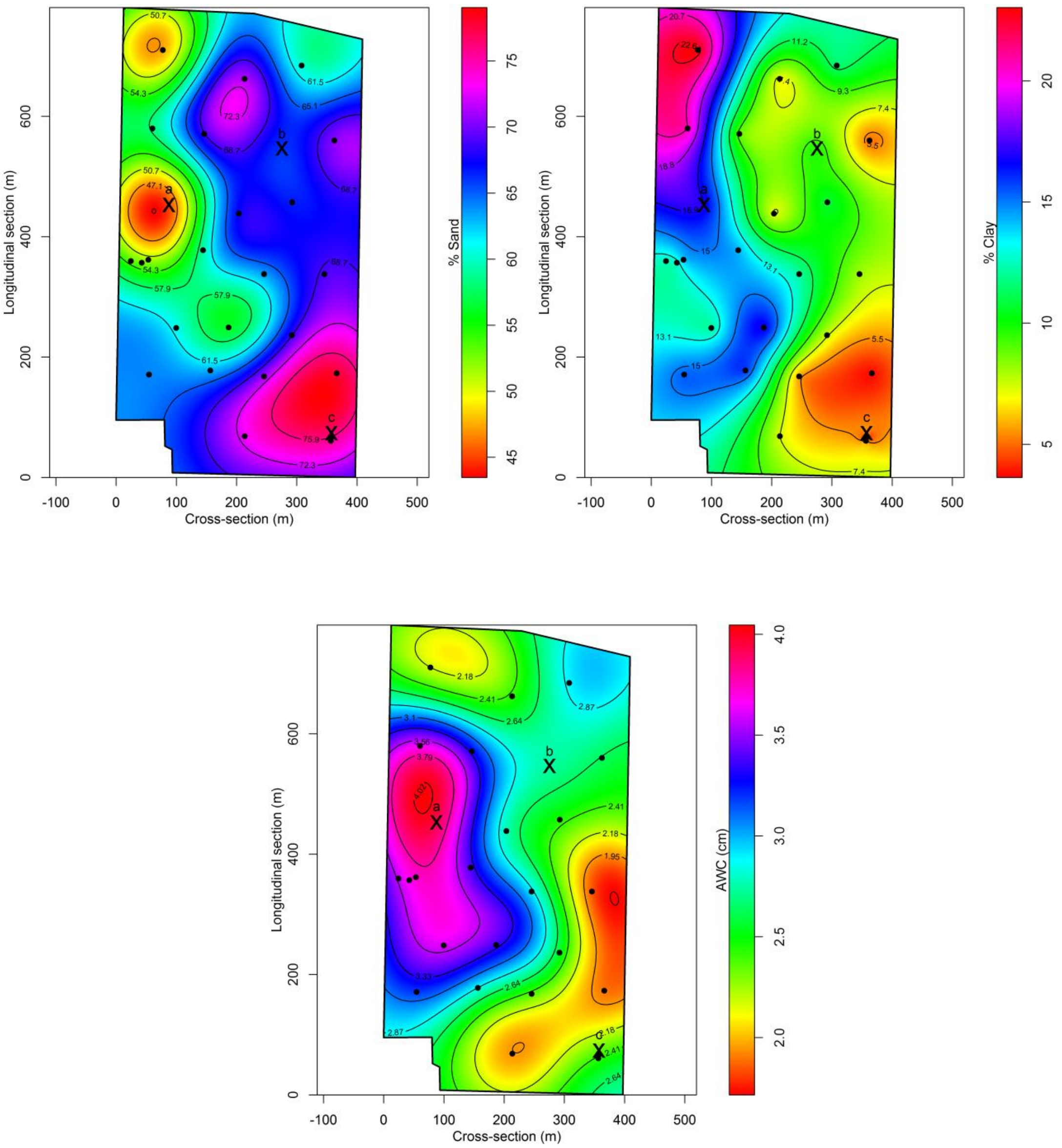


**Figure 3.3. Mapped soil parameters (% Sand, % Clay and available water content (AWC)) of the experimental setup (mean of the 25 and 50-cm samples at the 27 stations location). The three «Xs» represent the location of the contrasting samples (a, b and c) (represented in Figure 3.1 and Figure 3.2).**

**Table 3.I : Goodness of fit criteria used for each geostatistical method of different soil parameters (% Sand, % Clay and AWC) (means of the 25 and 50-cm samples) ($N_{25cm}$=27, $N_{50cm}$=27)**

| | | Criteria‡ | | | | |
|---|---|---|---|---|---|---|
| **Parameters** | **Methods†** | **ME** | **RMSE** | **Slope** | **Intercept** | **$R^2$** |
| **% Sand** | **OK** | -0.20 | 9.32 | 0.82 | 11.26 | 0.26 |
| | **IDW (p = 0.5)** | -0.03 | 10.03 | 2.76 | -112.89 | 0.22 |
| | **IDW (p = 1)** | -0.11 | 9.17 | 1.35 | -22.80 | 0.29 |
| | **IDW (p = 2)** | 0.02 | 8.90 | 0.96 | 2.82 | 0.31 |
| | **TPS** | -0.27 | 10.49 | 0.53 | 29.73 | 0.20 |
| **% Clay** | **OK** | 0.28 | 3.83 | 0.92 | 1.13 | 0.42 |
| | **IDW (p = 0.5)** | 0.10 | 4.71 | 2.79 | -19.26 | 0.19 |
| | **IDW (p = 1)** | 0.28 | 4.34 | 1.45 | -4.51 | 0.28 |
| | **IDW (p = 2)** | 0.33 | 4.05 | 1.16 | -1.35 | 0.35 |
| | **TPS** | 0.06 | 2.93 | 1.01 | -0.04 | 0.66 |
| **AWC§** | **OK** | -0.04 | 0.69 | 0.99 | -0.02 | 0.30 |
| | **IDW (p = 0.5)** | -0.03 | 0.80 | 2.43 | -4.14 | 0.09 |
| | **IDW (p = 1)** | -0.06 | 0.75 | 1.52 | -1.57 | 0.19 |
| | **IDW (p = 2)** | -0.10 | 0.73 | 1.11 | -0.42 | 0.24 |
| | **TPS** | -0.02 | 0.66 | 0.87 | 0.35 | 0.37 |

†OK, ordinary kriging; IDW, inverse distance weighting; TPS, thin plate splines
‡ME, mean error; RMSE, root mean square error
§AWC, available water content

### 3.2.2. Temporal Stability of SWT

Figure 3.4 presents Spearman coefficients from July 12 to August 22. The initial value on July 12 was chosen to reduce measurements variability due to the tensiometers installation. This date represents the second irrigation triggering following tensiometers installation.

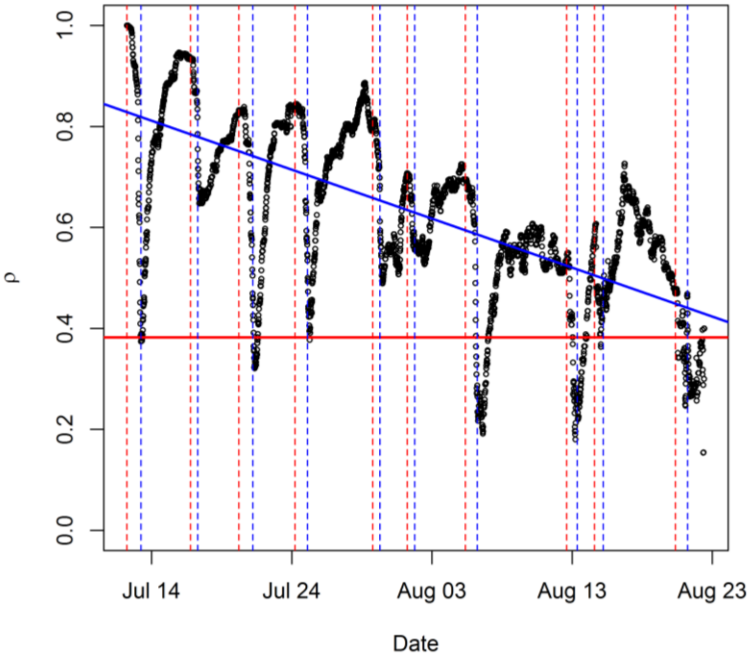


**Figure 3.4. Spearman coefficient ($\rho$) between soil water tension (SWT) measurements (means of the 25 and 50-cm tensiometers) with each location (27) from July 12 and SWT measurements to August 22. Points above the red line mean that SWT measurements are significantly temporally persistent at 5% level of a two-tailed test. Blue line represents the linear regression of $\rho$. Red and blue dashed lines refer to irrigation start and stop times, respectively.**

Spearman coefficient evolution shows that SWT tend to be temporally stable within a month and a half which means that highest, lowest and mean SWT measurements tended to occur at the same locations in this period. Furthermore, just after irrigation started, SWT measurements tended to be randomized. This could probably be explained by the variation of the waterfront, the tensiometer locations and the position of the micro-sprinkler. After the end of the irrigation, rank correlation tends to increase until the next irrigation. This means that the driest and the wettest field locations tended to come back at their initial rank situation after the end of irrigation. However, decrease of Spearman correlation in time is probably governed by the hysteresis phenomenon. Thus, the spatial pattern of SWT is steady in time over a month and a half, but appears to be variable beyond that.

The autocorrelation function was used to determine the SWT measurements stability within the test duration (Figure 3.5). Given that a trend was observable for the time series, a linear regression model was made to detrend the SWT data and then, used the residual values for the autocorrelation function. For each location, SWT was correlated but tended to oscillate when irrigation occurred. This means that SWT tended to be less correlated during the wetting phase, probably caused by the differences in soil parameters and the position of the probes regarding the wetted bulb.

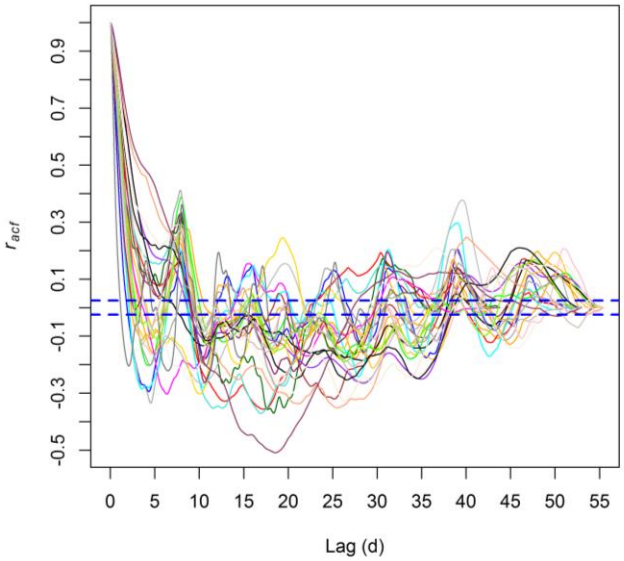


**Figure 3.5. Autocorrelation coefficients for soil water tension (SWT) measurements (means of the 25 and 50-cm tensiometers) for each location (27). Values beyond the dashed blue lines mean significant temporal stability at 5% level of significance.**

### 3.2.3. Spatial variability of SWT

Variographic analysis was first used to determine if SWT measurements were spatially structured. Cross-validation showed that SWT were either uncorrelated or poorly correlated. It is consistent with Saddiq et al. (1985) who found low spatial dependence (< 6m) of SWT in a clay loam soil under trickle irrigation and Chile pepper production. Their study showed that SWT variability was principally due to irrigation method, time of measurements after water applications and the mean value of SWT. However, as SWT measurements were randomly distributed and that continuous measurements were available in this study, distributions were determined using the arithmetic mean of field SWT values. We used Kolmogorov-Smirnov test to compare empirical distributions to theoretical normal and log-normal distribution. Results showed that SWT began following a log-normal distribution several hours after the end of the irrigation and until the other irrigation. However, SWT was also normally distributed but after a longer period following irrigation. During and just after irrigation, SWT was neither normally nor log normally distributed. Hendrickx & Wierenga (1990) and Webster (1966) also used log-normal distributions to analyze SWT variability. Between each irrigation event, same mean SWT value distributions were compared in pairs with empirical distribution using Kolmogov-Smirnov test. Even if distributions tend to be more and more different after each irrigation, same average field SWT distributions obtained for each irrigation interval were not significantly different. All measurements were then put together to form a global distribution at each desired mean SWT. Results showed that standard deviation of SWT tended to increase when mean field SWT increase. This means that the range of SWT measurements increases when the soil dries which is consistent with the findings of Hendrickx & Wierenga (1990). As no values were measured over an average field SWT of -45 kPa, lower mean field SWT distributions were simulated using the log standard deviation at -45 kPa. Figure 3.6 presents the fitted probability density function (PDF) at different field arithmetic means SWT.

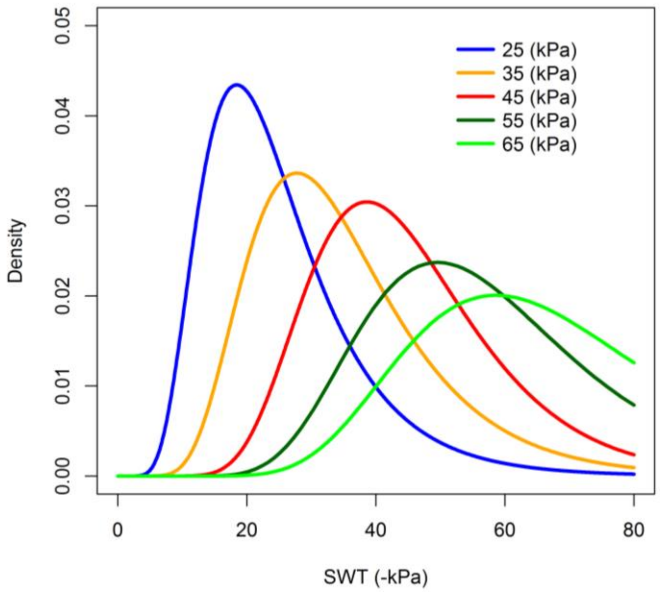


**Figure 3.6. Fitted probability density function (PDF) of different arithmetic means of all field soil water tension (SWT) measurement (means of the 25 and 50 cm tensiometers) with each location (27) (to initiate irrigation; corresponding values in legend).**

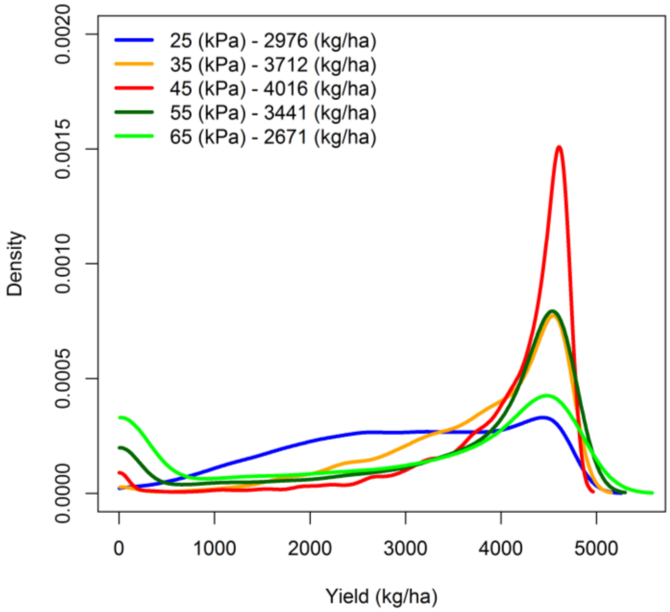


**Figure 3.7. Simulated probability density function (PDF) of yield obtained with different arithmetic means of field soil water tension (SWT) measurement**

**(means of the 25 and 50 cm tensiometers) with each location (27) to initiate irrigation (corresponding values in legend).**

### 3.2.4. Economic Analysis

Using different fitted PDF at different field arithmetic mean SWT and the yield SWT response curve derived by Collin et al. (2017), PDF of yield were simulated (Figure 3.7). It indicates that average field yield is dependent of field SWT and still optimal when irrigation start at -45 kPa. Moreover, it shows that a 30% yield drop can be obtained by running a too wet or too dry irrigation threshold (-25 or -65 kPa). Given this SWT measurement variability and the yield respond to SWT, two questions can be raised. First, does the addition of a tensiometers station would improve net margins in comparison to the current irrigation management, and second, should we put more tensiometers station to best capture the overall variability. Figure 3.8 gives the answer to these questions. According to the initial economic assumptions and the yield response to SWT (Figure 3.8 (a)), Monte Carlo simulations show that adding one station to a 30-ha field increase the additional net margin if the irrigation is managed with an average field SWT threshold of -45 kPa (means of 25-50-cm tensiometers) but decrease the additional net margin if the irrigation management is too wet (-35 kPa) or too dry (-55 kPa). However, results show that producers should use five stations of tensiometers in a 30-ha field to maximize the additional net margin. Obviously, the response of the additional net margin and the optimal number of stations will vary with the almond price, the cost of water needed to achieve maximum yields, and the cost of the stations needed to capture SWT variability (Figure 3.8 (b,c)). Certainly, if almond price increased, it would be advantageous to increase the number of stations to have a better view of the SWT variability, but in the opposite if it decreased, the optimal number of stations would be lower. In parallel, if the cost of water increases, growers should use a dryer SWT threshold to manage their irrigation and then use less water. This model can be adjusted as needed with other economic assumptions and can easily be used to predict the best SWT threshold to use in irrigation triggering according to the current economic reality.

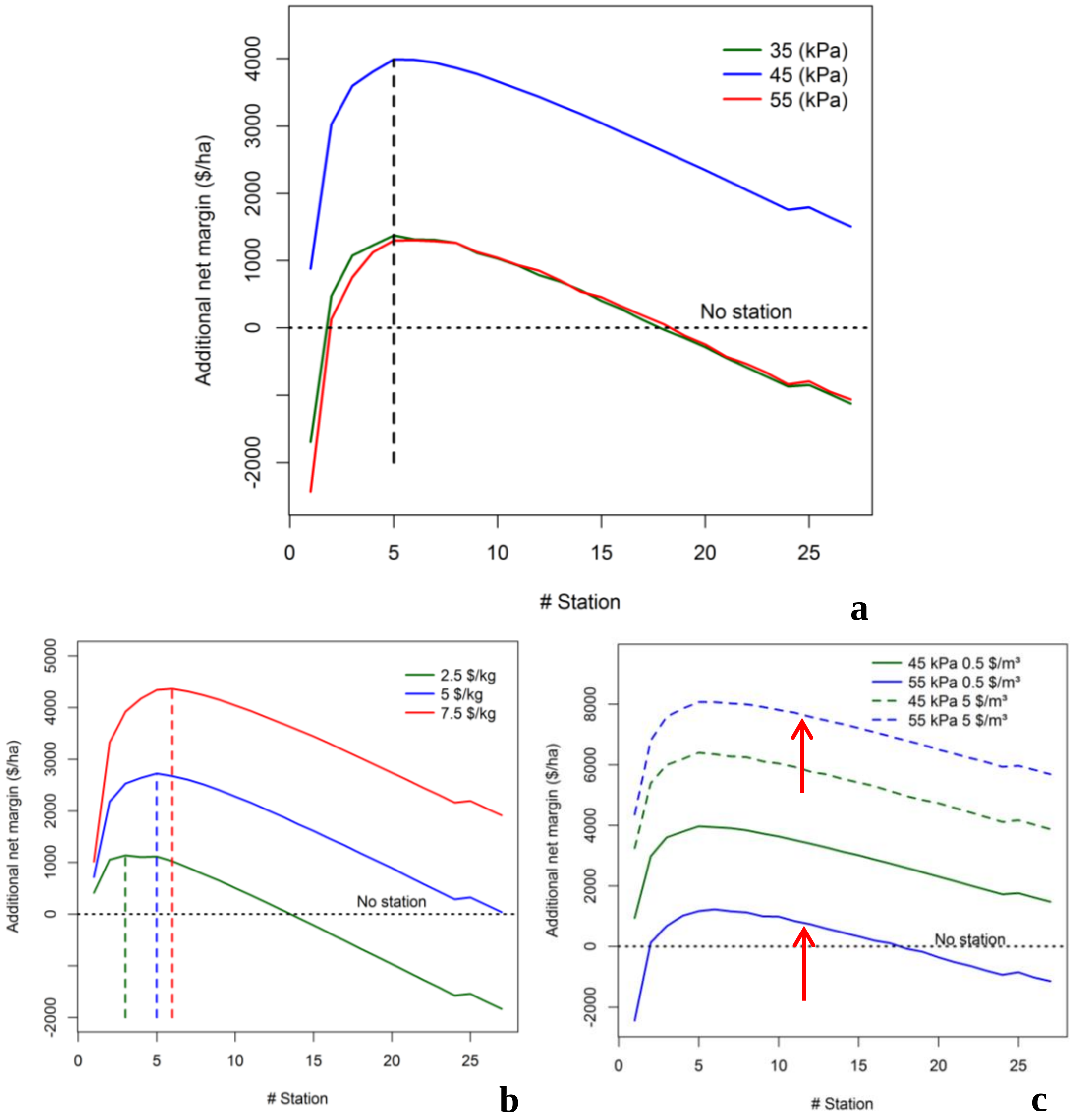


**Figure 3.8. Simulated additional net margins related to the number of stations according to: (a) SWT threshold management, (b) almond price and (c) water price.**

## 3.3. Conclusion

According to the results of this study, we concluded that the SWT pattern is stable within a month and a half and that it is correlated in time over the experimental period at the same location. Furthermore, they were not spatially structured, but were rather randomly distributed. SWT followed a log-normal distribution between irrigation periods. Empirical distributions followed the same distributions at same arithmetic mean SWT at different times during the experiment. Variance of SWT measurements increased when average field SWT decreased (lower tension, drier conditions). That shows that difference between measurements increases as the soil dries up. This indicates that as the soil dried up, the measurement dispersion increased. With current economic parameters (water, almond and SWT station prices) and the methods used in this study, growers should use 5 stations per field of 30 ha to optimize their profits. They also should use a threshold of -45 kPa using mean tension of tensiometres at 25 and 50 cm placed in the wetted irrigated soil. Finally, this study provided a tool to predict the soil water tension threshold and the number of stations to use according to those economical parameters.

## 3.4. Acknowledgements

We would like to thank Natural Science and Engineering Research Council of Canada (NSERC) and Le Fonds de Recherche Nature et Technologies du Québec for their financial contributions. We also recognize the technical and financial support of Hortau Inc., and undergraduates, graduates and professionals who contributed to this research with the laboratory work.

## 3.5. References

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith. 1998. "Crop Evapotranspiration: Guidelines for Computing Crop Requirements." *Irrigation and Drainage Paper No. 56, FAO* (56):300.

Almond Board of California. 2015. "Almonds and Water 101."

Almond Board of California. 2016. "California Almond Industry Facts."

California Department of Water Resources. 2014. "Water Year 2014 Ends as 3rd Driest in Precipitation."

CDFA, USDA, and NASS. 2016. *2016 California Almond Nursery Sales Report*.

Centre d'expertise en analyse environnementale du Québec. 2015. "Détermination de La Granulométrie, MA. 100 - Gran. 2.0, Rév. 1." 16(révision 1):11 p.

Collin, G., J. Caron, J. Gallichand, and G. Létourneau. 2017. "Soil Water Tension Threshold for Almond Irrigation." *Communications in Soil Science and Plant Analysis* (submitted).

Connell, J. H. et al. 2012. "Sample Cost to Establish an Orchard and Produce." *Current*.

Conover, W. J. 1980. *Practical Nonparametric Statistics*. 2nd ed. edited by John Wiley & Sons.

Dane, J. H. and J. W. Hopmans. 2002. "Pressure Cell." Pp. 684–92 in *Methods of Soil Analysis. Part 4-Physical Methods*. Soil Science Society of America Book series.

Delignette-Muller, M. L., C. Dutang, R. Pouillot, and J. B. Denis. 2016. "Package 'Fitdistrplus' - Help to Fit of a Parametric Distribution to Non-Censored or Censored Data." (1).

Dhillon, R., V. Udompetaikul, F. Rojo, and J. Roach. 2014. "Detection of Plant Water Stress Using Leaf Temperature and Microclimatic Measurements in Almond, Walnut, and Grape Crops." *Transactions of the ASABE* 57(1):297–304.

Fereres, E. 1996. "Irrigation Scheduling of Horticultural Crops." *II International Symposium on Irrigation of Horticultural Crops* 449:253–58.

Fereres, E. and D. A. Goldhamer. 2003. "Suitability of Stem Diameter Variations and Water Potential as Indicators for Irrigation Scheduling of Almond Trees." *Journal of Horticultural Science and Biotechnology* 78(2):139–44.

Fuentes, S., M. Mahadevan, M. Bonada, M. A. Skewes, and J. W. Cox. 2013. "Night-

Time Sap Flow Is Parabolically Linked to Midday Water Potential for Field-Grown Almond Trees." *Irrigation Science* 31(6):1265–76.

Fulton, A., R. Buchner, B. Olson, L. Schwankl, C. Gilles, N. Bertagna, J. Walton, K. Shackel, 2001. "Rapid Equilibration of Leaf and Stem Water Potential under Field Conditions in Almonds, Walnuts, and Prunes." *HortTechnology* 11(4):609–15.

Fulton, A., J. Grant, R. Buchner, and J. Connell. 2014. "Using the Pressure Chamber for Irrigation Management in Walnut, Almond, and Prune." *ANR Publication 8503* 1–27.

Hendrickx, J. M. H. and P. J. Wierenga. 1990. "Variability of Soil Water Tension in a Trickle Irrigated Chile Pepper Field." *Irrigation Science* 11(1):23–30.

Hiemstra, P. 2015. "Package ' Automap ' - Automatic Interpolation Package."

Howitt, R., J. Medellín-azuara, and D. Macewan. 2015. "Economic Analysis of the 2015 Drought for California Agriculture." *Center for Watershed Sciences. University of California, Davis, California* 20p.

Jones, H. G. 2004. "Irrigation Scheduling: Advantages and Pitfalls of Plant-Based Methods." *Journal of Experimental Botany* 55(407):2427–36.

Maes, W. H. and K. Steppe. 2012. "Estimating Evapotranspiration and Drought Stress with Ground-Based Thermal Remote Sensing in Agriculture: A Review." *Journal of Experimental Botany* 63(13):4671–4712.

Metropolis, N. and S. Ulam. 1949. "The Monte Carlo Method." *Journal of the American Statistical Association* 44(247):335–41.

Naor, A. 2006. "Irrigation Scheduling and Evaluation of Tree Water Status in Deciduosus Orchads.pdf." 32:111–65.

Nortes, P. A., A. Baille, G. Egea, M. M. González-Real, and R. Domingo. 2009. "Comparison of Almond Tree Transpiration Determined by Sap Flow Measurements and Lysimetry." *Acta Horticulturae* 846:359–66.

Nychka, D., R. Furrer, J. Paige, and S. Sain. 2016. "Package 'fields' - Tools for Spatial Data."

O'Green, T., J. Deng, P. Hartsough, and S. Wilson. 2016. "California Soil Survey."

Pebesma, E. and B. Graeler. 2015. "Package ' Gstat ' - Spatial and Spatio-Temporal Geosttistical Modelling, Prediction and Simulation."

Van Pelt, R. S. and P. J. Wierenga. 2001. "Temporal Stability of Spatially Measured Soil Matric Potential Probability Density Function." *Soil Science Society of*

*America Journal* 65(3):668.

Reynolds, W. D. 2008. “Saturated Hydraulic Properties : Laboratory Methods.” Pp. 1013–24 in *Soil Sampling and Methods of Analysis*, edited by C. M.R. and E. G. Gregorich. Canadian Society of Soil Science, CRC Press.

Rolston, D. E., J. W. Biggar, and H. I. Nightingale. 1991. “Temporal Persistence of Spatial Soil-Water Patterns under Trickle Irrigation.” *Irrigation Science* 12(4):181–86.

Romero, R., J. L. Muriel, and I. Garcia. 2009. “Automatic Irrigation System in Almonds and Walnuts Trees Based on Sap Flow Measurements.” *Acta Horticulturae* 846:135–42.

Saddiq, M. H., P. J. Wierenga, J. M. H. Hendrickx, and M. Y. Hussain. 1985. “Spatial Variability of Soil Water Tension in an Irrigated Soil.” 126–32.

Shackel, K. A. et al. 1997. “Plant Water Status as an Index of Irrigation Need in Deciduous Fruit Trees.” *HortTechnology* 7(1):23–29.

Snyder, R. L., B. J. Lanini, D. A. Shaw, and W. O. Pruit. 1987. “Using Reference Evapotranspiration (ET0) and Crop Coefficients to Estimate Crop Evapotranspiration (Etc) for Trees and Vines” edited by U. of California.

USDA/NASS. 2015. *Agricultural Statistics 2015*.

Webster, R. 1966. “The Measurement of Soil Water Tension in the Field.” *New Phytologist* 65(2):249–58.

Wilks, D. S. 2006. *Statistical Methods in the Atmospheric Sciences*. 2nd Editio. Elsevier Academic Press Publications. San Diego, CA.

Williams, L. E. and F. J. Araujo. 2002. “Correlations among Predawn Leaf, Midday Leaf, and Midday Stem Water Potential and Their Correlations with Other Measures of Soil and Plant Water Status in Vitis Vinifera.” *J. Amer. Soc. Hort. Sci.* 127(3):448–54.

# Conclusion générale

L'État de Californie est le plus grand producteur d'amandes dans le monde. Cette production génère plus de 21 milliards de dollars en revenu brut pour l'économie californienne et plus de 100 000 emplois. La majorité de cette production est située dans la Vallée Centrale, une région où le régime pluvial est faible. Bien que cette culture soit considérée résistante à la sécheresse, celle-ci peut nécessiter jusqu'à 1500 mm d'eau tout au long de son cycle de production pour obtenir des rendements acceptables. Une utilisation en eau combinée à un réapprovisionnement faible durant une longue sécheresse peut causer de grands problèmes environnementaux. Bien que plusieurs méthodes de gestion de l'irrigation ont été mises de l'avant dans les dernières années, spécifiquement dans la culture de l'amande, ces techniques n'étaient basées que sur des calculs de besoins en eau globaux ou de mesure de stress ponctuelle. Parallèlement, dans les dernières années, plusieurs recherches basées sur des mesures en continu du potentiel matriciel dans différentes cultures ont permis d'économiser de l'eau et d'augmenter les rendements. Dans la même optique, ce projet avait pour but d'amener une nouvelle méthode de gestion de l'irrigation dans une culture et une région critique au niveau de la consommation en eau.

Cette étude a permis de définir différentes recommandations vis-à-vis l'utilisation des tensiomètres comme outil de gestion de l'irrigation dans la production d'amandes en Californie. Celle-ci a démontré que l'utilisation d'un seuil de tension moyen à 25-50 cm de -45 kPa permet d'économiser environ 20% d'eau en comparaison avec les méthodes actuelles de gestion d'irrigation, et ce, sans affecter la productivité des vergers. L'analyse a aussi permis de montrer l'effet négatif que peut avoir une régie d'irrigation trop humide ou trop sèche sur les rendements et a fait ressortir qu'une attention particulière devrait être effectuée concernant le choix des coefficients de culture pour l'estimation de l'évapotranspiration.

Les essais ont permis d'observer que les mesures du potentiel matriciel de l'eau du sol ont tendance à ne pas être fortement corrélé au niveau spatial, et ont plutôt tendance à suivre une distribution aléatoire lognormal à l'échelle d'un champ de

30 ha entre les périodes d’irrigation. Bien que ces mesures ne soient pas corrélées spatialement, l’étude a montré une corrélation temporelle au niveau du patron des mesures s’étalant sur une période d’environ 1 mois et demi. L’expérience a permis la conception d’un outil pour ajuster les seuils de tension et le nombre de stations à utiliser par champ en fonction de différents critères économiques. Avec cette méthodes proposée, il a été possible d’établir que les producteurs devraient utiliser la moyenne de tension à 25-50 cm de 5 stations par champ de 30 ha pour maximiser leur marge additionnelle nette selon les aspects économiques actuels. Finalement, il est possible de croire que ces résultats permettront de diminuer l’utilisation en eau et d’améliorer la productivité de la culture d’amandes en Californie.