# Eco-efficience des itinéraires techniques viticoles : intérêt et adaptations de l'analyse du cycle de vie pour la prise en compte des spécificités de la viticulture de qualité

Christel Renaud-Gentié

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## Christel RENAUD-GENTIÉ

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***grade de Docteur de l'Université d'Angers***
*sous le label de L'Université Nantes Angers Le Mans*

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## Application aux itinéraires techniques de production de raisins de Chenin blanc pour vins blancs secs d'AOC en Moyenne Vallée de la Loire

## JURY

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|---|---|
| Rapporteurs : | **Carole SINFORT**, Professeur, Montpellier Supagro<br>**Jacques WERY**, Professeur, Montpellier Supagro |
| Examinateurs : | **Benoît GABRIELLE**, Professeur, AgroParisTech<br>**Patrick MOURON**, Chercheur, Agroscope |
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L'Université Nantes Angers Le Mans

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# ECO-EFFICIENCE DES ITINERAIRES TECHNIQUES VITICOLES : INTERETS ET ADAPTATIONS DE L'ANALYSE DU CYCLE DE VIE POUR LA PRISE EN COMPTE DES SPECIFICITES DE LA VITICULTURE DE QUALITE

## APPLICATION AUX ITINERAIRES TECHNIQUES DE PRODUCTION DE RAISINS DE CHENIN BLANC POUR VINS BLANCS SECS D'AOC EN MOYENNE VALLEE DE LA LOIRE

## *ECO-EFFICIENCY OF VINEYARD TECHNICAL MANAGEMENT ROUTES: INTERESTS AND ADAPTATIONS OF LIFE CYCLE ASSESSMENT TO ACCOUNT FOR SPECIFICITIES OF QUALITY VITICULTURE*

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## 1 INTRODUCTION

Les filières viticoles sont soumises à des pressions sociale, réglementaire et économique croissantes pour adopter des pratiques durables. Elles sont directement concernées en France, par un des objectifs de la politique environnementale nationale qui est la réduction de 50% de l'utilisation des pesticides entre 2008 et 2018. Une nouvelle exigence d'affichage environnemental sur les produits de grande consommation (dont les vins), basé sur l'Analyse du Cycle de Vie (ACV) est, par ailleurs, en projet à l'échelle européenne (Commission 2014b). Les vignerons doivent donc poursuivre l'adoption de techniques plus respectueuses de l'environnement tout en assurant le maintien de la qualité organoleptique de leurs vins. L'aspect qualitatif est particulièrement important dans les vignobles d'AOC, qui représentent plus de 60% des vignobles français et 80% en Val de Loire.

L'évolution du climat de la terre impacte la composition des raisins (Neethling et al. 2011) et de ce fait la typicité des vins (Van Leeuwen et al. 2009). L'adaptation des techniques viticoles à ces changements a déjà commencé mais l'évolution rapide des températures et de la disponibilité en eau devrait induire dans les années à venir la nécessité de modifications plus profondes (Lereboullet et al. 2013) et probablement diverses dans les techniques, les choix variétaux et la localisation des vignobles à différentes échelles et à des intensités variables selon les régions du globe (Jones et al. 2005). Le risque d'accroissement de certains impacts sur l'environnement, comme la consommation de ressources en eau pour l'irrigation ou le changement d'usage de sols dans le cas de déplacement de vignobles vers des zones non cultivées aujourd'hui, est à envisager (Hannah et al. 2013). Ces évolutions, ainsi que la diversité des situations géo-pédologiques et socio-économiques, déterminent, par ailleurs, une diversité d'itinéraires techniques qu'il est important de caractériser pour pouvoir réfléchir à l'avenir de la viticulture.

Apporter des éléments utiles aux choix des itinéraires techniques et des techniques viticoles répondant au double objectif qualitatif et environnemental est une des cibles que s'est fixé l'unité de recherche UPSP GRAPPE du Groupe ESA, dans le cadre de l'UMT VINITERA[1]. Cette thèse vise à poser des fondements scientifiques pour cet accompagnement de la filière viticole dans sa dynamique de progrès en explorant l'intérêt de la méthode de l'ACV pour répondre à cet objectif. Elle s'insère dans le cadre de la problématique du projet scientifique de l'UMT VINITERA « Comment concevoir et évaluer des systèmes vitivinicoles innovants en réponse à un contexte changeant ? ».

L'ACV est, en effet, parmi les nombreuses méthodes permettant d'évaluer l'impact d'une production agricole sur l'environnement (Bockstaller et al. 2009; Payraudeau and Vanderwerf 2005), celle qui permet actuellement de réaliser le bilan le plus exhaustif. En évaluant toutes les phases du processus de production, elle permet d'éviter que les améliorations environnementales locales ne soient que la résultante d'un déplacement des charges polluantes (Jolliet et al. 2010b). La méthodologie ACV a déjà été mise en œuvre dans la filière vitivinicole (Petti et al. 2010; Benedetto et al. 2013), mais dans d'autres buts que le choix des techniques viticoles (quantification de l'impact d'une bouteille de vin, identification des grandes phases du cycle de vie les plus contributives, comparaison des impacts entre vin biologique et vin conventionnel, évaluation des voies d'amélioration à l'échelle régionale). La thèse défendue dans ce manuscrit est que l'ACV est un outil pertinent et utile pour l'évaluation et l'optimisation fine des performances environnementales des itinéraires techniques de production de raisins de qualité dans la mesure où l'on dispose de données d'entrée fiables et suffisantes.

Il est pour cela notamment nécessaire de vérifier dans quelle mesure la méthode est sensible à la variabilité des milieux, des pratiques et des millésimes à l'échelle parcellaire. Il est utile aussi de contribuer à l'enrichir sur le plan méthodologique, notamment concernant la prise en compte des phases non productives, la question clé en viticulture de la prise en compte des impacts des émissions de pesticides au champ, la vigne faisant partie des cultures fortes consommatrices de ces substances (Aubertot et al. 2005b)

Après cette introduction, des éléments de contexte amèneront à poser la problématique de la thèse dont la question centrale est la suivante : **A quelles conditions l'ACV est-elle une méthode appropriée à l'évaluation environnementale des itinéraires techniques viticoles de production de vins de qualité à l'échelle parcellaire à des fins de choix des techniques?** Dans le chapitre 1, nous présenterons comment nous avons caractérisé la diversité régionale des itinéraires viticoles pour la constitution d'un jeu de cas représentatifs et contrastés, préalable indispensable à la mise en œuvre des ACV pour notre étude.

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Le chapitre 2 abordera la résolution d'un verrou méthodologique pour l'ACV des itinéraires techniques viticoles (ITKv), la modélisation des émissions de pesticides au champ. Nous présenterons dans le chapitre 3 le point central de la thèse, la description du cadre méthodologique de l'ACV des ITKv et son application aux cinq cas contrastés décrits dans le chapitre 1. Le chapitre 4 permettra d'évaluer l'effet du millésime sur les performances environnementales d'un ITKv. Nous explorerons, dans le chapitre 5, une modalité de prise en compte de l'objectif qualitatif des raisins dans l'ACV des ITKv. Enfin dans la discussion générale, nous dresserons une synthèse des résultats, discuterons les apports et limites de nos travaux avant de proposer des perspectives pour l'application et les recherches futures.

# 2 CONTEXTE ET ENJEUX

## 2.1 LES POLITIQUES ENVIRONNEMENTALES INTRODUISENT L'ACV DANS LES FILIERES AGRICOLES.

La protection de l'environnement est considérée comme importante ou très importante par 95% des citoyens de l'Union Européenne (Commission 2014a). Elle est devenue une question omniprésente dans la société européenne du début du 21ème siècle, notamment du fait des atteintes à l'environnement de plus en plus graves rappelées très récemment avec force par le Groupe International des Experts du Climat (GIEC)(IPCC 2014). Des mesures pour la prise en compte des questions environnementales ont pourtant été établies au niveau institutionnel dans de nombreux pays (Poupard and Bossat 2013). Dans ce contexte, un nouveau cadre législatif européen pour la production et la consommation durables est prévu dans le programme d'action de l'Union Européenne. Il sera notamment fondé sur des indicateurs de cycle de vie (Commission 2014c).

De nombreux pays constituent actuellement des bases de données d'inventaires d'analyse du Cycle de Vie (ICV) de leurs produits agricoles et alimentaires comme l'Australie (Eady et al. 2013a) ou le Chili (Emhart et al. 2014) dans un objectif d'affichage environnemental d'aide à la détermination de politiques publiques ou d'accompagnement des entreprises. La France, précurseur sur le sujet, a su sensibiliser ses partenaires européens aux enjeux de l'affichage environnemental et le programme d'action général de l'Union Européenne pour l'environnement à l'horizon 2020 (Commission 2014c) fait clairement mention dans son objectif 35, pour les consommateurs, d' « un étiquetage clair et cohérent, y compris en ce qui concerne les allégations environnementales ». Le projet de mise en place d'une empreinte environnementale des produits s'est traduit, entre autres, par l'établissement à l'échelle européenne de cadres méthodologiques publiés en 2014.

En effet, la France, suite à la conférence nationale "Grenelle de l'environnement" en 2007, s'est notamment dotée de deux textes de lois dites Grenelle 1 et 2. Une partie des mesures de la loi dite "Grenelle 1" concerne l'agriculture et, de ce fait, la viticulture avec trois objectifs majeurs:

- la diminution de la consommation d'intrants phytosanitaires de 50% entre 2008 et 2018
- le passage de la proportion d'exploitations agricoles sous cahier des charges de l'agriculture biologique à 20% en 2020
- une limitation de la dépendance énergétique des exploitations agricoles

La loi dite "Grenelle 2" mentionne, quant à elle, le projet d'appliquer l'affichage environnemental à tous les produits de grande consommation, ce qui inclut les produits d'origine agricole, dont le vin. Ce projet ne s'est, à ce jour, pas encore traduit par une obligation. L'affichage environnemental tel qu'il est envisagé en France est basé sur un calcul d'impacts par ACV (Vergez 2012). Ceci a amené les filières agricoles à se préparer à cette éventualité par l'établissement d'une base de données d'ICV de leurs produits à travers le projet AGRIBALYSE® (Colomb et al. 2014). Ce projet a, d'autre part, permis de sensibiliser les filières agricoles à la pensée cycle de vie par le biais de leurs instituts techniques, et à ces derniers de commencer à s'approprier la méthode de l'ACV.

Enfin, l'Organisation Mondiale de la Vigne et du Vin (OIV) souhaite harmoniser la mesure des émissions des produits et procédés liés à la production du vin en adoptant un protocole unique basé sur la méthodologie de l'ACV (Benedetto et al. 2013)

## 2.2 LA VITICULTURE, ACTIVITE QUI IMPACTE L'ENVIRONNEMENT

Les atteintes à l'environnement liées aux pratiques agricoles issues des progrès techniques de la seconde moitié du XX$^{ème}$ siècle sont apparues de plus en plus évidentes au début du XXI$^{ème}$ siècle. A l'échelle internationale, malgré une évolution des pratiques dans certaines régions et chez une partie des producteurs, le management environnemental demeure inadapté aux enjeux (Christ and Burritt 2013). La vigne, sensible à de nombreux bio-agresseurs, fait partie des cultures les plus fortes consommatrices de pesticides (Aubertot et al. 2005b), le chiffre de 20kg/ha/an à l'échelle de l'union Européenne en 2003 est donné par Muhtman (2007) (dont 15kg/ha/an de soufre élémentaire). En France, 80% des pesticides appliqués par la viticulture sont des fongicides (Mézière et al. 2009). Comme le montre, par exemple, le rapport 2008 du réseau de suivi des pesticides dans les eaux en Région Bourgogne (DIREN et al. 2008), les cours d'eaux situés en aval des zones viticoles sont souvent les plus pollués et les points de contrôles des eaux souterraines en zones viticoles ne sont jamais indemnes de résidus, contrairement à d'autres zones agricoles ou forestières limitrophes. Bedos et al. (2002) estiment les pertes engendrées par la volatilisation des produits phytosanitaires appliqués en agriculture de 10 à 90 % des quantités épandues. Des pesticides sont par ailleurs retrouvés dans toutes les phases atmosphériques (Aubertot et al. 2005b), tant dans les zones de cultures que dans les zones habitées (Ducroz 2006). Par la suite, la re-déposition de ces molécules dans les eaux de surface est un phénomène non négligeable (Warren et al. 2003).

L'application répétée de fongicides à base de cuivre durant des décennies a par ailleurs causé l'accumulation du cuivre dans différents sols viticoles dans le monde à des teneurs parfois très importantes (Brun et al. 1998). Des phénomènes de biotoxicité pour les organismes du sol sont alors observés (Eijsackers et al. 2005; Fernández-Calviño et al. 2010; Mackie et al. 2012). Les sols viticoles à structures battantes ou sans couverture végétative sont aussi affectés par l'érosion dans les vignobles en pente (Jammart et al. 2003). Ceci occasionne des coûts spécifiques liés à la récupération de la terre érodée et à la diminution de la qualité du sol pour les vignerons (Herbreteau et al. 2003), mais aussi pour les collectivités territoriales gérant les zones avales aux vignobles (Jammart et al. 2003). La structure des sols viticoles les plus meubles est aussi atteinte par le passage répété des engins (Polge de Combret-Champart et al. 2013).

Les activités agricoles sont responsables de 10 à 12 % des émissions de gaz à effet de serre (GES) attribuées aux activités humaines dans le monde (Burney et al. 2010) et estimées à 20% des émissions totales de GES en France (Pellerin et al. 2014). La part des activités viticoles dans ces émissions n'est pas quantifiée à notre connaissance, cependant, Rugani et al.(2013) ont réalisé une revue bibliographique internationale de 29 études quantifiant l'empreinte carbone d'une bouteille de vin calculée à partir de la production de gaz à effet de serre (GES) au long du cycle de vie de la bouteille de vin, soit de la plantation du vignoble à la fin de vie de la bouteille. Les émissions de GES sont de 2,17 +/-1,34 kg eq.$CO_2$ par bouteille. La phase de production viticole, incluant la phase de plantation compte pour 0,45 +/- 0,38 kg eq $CO_2$ par bouteille (une voiture émet en moyenne 0,140 kg eq. $CO_2$/km parcouru). En multipliant cette valeur par la production française de vin de 2011 (50,7Mhl (OIV 2013a)), on obtient un ordre de grandeur de 3+/-2.6 Mt eq $CO_2$ sur les 105 Mt eq $CO_2$ attribuées à l'agriculture française (Pellerin et al. 2014). Ceci n'est qu'un ordre de grandeur indicatif, les modes de calcul entre les deux valeurs étant très différents.

Enfin, l'utilisation de ressources non renouvelables en viticulture est liée notamment à la mécanisation des opérations et aux transports mais aussi à la fabrication de certains intrants. Elle concerne principalement les énergies fossiles et les minerais entrant dans la fabrication des machines (Aranda et al. 2005)

## 2.3 LA FILIERE VITICOLE INTEGRE LA QUESTION ENVIRONNEMENTALE

Dans ce contexte, les filières viticoles de nombreux vignobles du monde entendent la nécessité de continuer à progresser sur leurs performances environnementales (Cordano et al. 2010; Belis-Bergouignan and Cazals 2006; Gabzdylova et al. 2009). Les filières viticoles des pays les plus récemment arrivés sur la scène viticole internationale communiquent vers les marchés sur leurs performances environnementales (Vecchio 2013). En France, les mentalités des prescripteurs de techniques viticoles ont considérablement évolué depuis la fin des trente glorieuses (1945-1973) comme le montrent les travaux de Schott et al. (2004) en Champagne, où la mise en avant des solutions d'entretien du sol "tout chimique" sans aucune préoccupation environnementale des années 70, a laissé place, trente ans après, à une recherche de toutes les solutions alternatives à l'utilisation de produits phytosanitaires, comme c'est d'ailleurs le cas dans l'ensemble du vignoble français (Heinzlé 2006). Des efforts ont, notamment, été engagés dans la filière avec l'élaboration d'un référentiel de production intégrée en viticulture coordonnée par l'institut technique de la vigne et du vin suite à la parution du rapport sur l'agriculture raisonnée commandé par le Ministère de l'Agriculture et de la Pêche en 2000 (Paillotin 2000).

Les vignerons ont, eux aussi, progressivement pris conscience de la nécessité de l'évolution de leurs pratiques vers plus de durabilité, notamment par une diminution des produits phytosanitaires, progrès qui nécessite au moins autant une évolution des mentalités et des méthodes de travail qu'une révolution technique (Boulanger-Fassier 2009; Walsdorff et al. 2005; Fassier-Boulanger 2014a). La parution du référentiel de production intégrée a amorcé la mise en place, dans différentes régions, d'associations de vignerons souhaitant appliquer la production intégrée dans le respect de ce cahier des charges. Toutefois ces démarches ont rencontré un succès limité notamment du fait de la difficulté à valoriser la démarche commercialement.

Cette prise de conscience correspond, notamment, à une nécessaire réponse à la rupture du lien de confiance qui existait entre les consommateurs et l'agriculture, suite aux crises sanitaires des années 90 (vache folle, listéria, dioxine dans les produits aviaires...) (Boulanger-Fassier 2014). Encore aujourd'hui, le risque alimentaire mentionné en premier par les français est celui "lié aux traitements (par exemple pesticides) sur les cultures", devant les « épidémies animales » ou la « présence de microbes ou de bactéries sur les produits alimentaires » (CREDOC 2011).

Le souhait de certains vignerons de faire évoluer leurs pratiques tient aussi à une prise de conscience, non encore généralisée (Nicourt and Girault 2009) des risques qu'eux et leurs salariés encourent lors de la manipulation des produits phytosanitaires, et que montrent quelques (trop rares) études épidémiologiques (Jas 2010). Une récente situation d'intoxication d'enfants lors d'un traitement d'une vigne voisine, fortement médiatisée en France, met par ailleurs les vignerons face au risque qu'encourent potentiellement les populations voisines des vignes lors des applications de substances actives.

L'engagement dans la viticulture biologique, encouragé par l'état en France, suite au Grenelle de l'environnement, a affiché une croissance proche de 100% (en surfaces certifiées) entre 2008 et 2012 en France et de 20 % par an (2011) à l'échelle mondiale (Agence-Bio 2013). Chez ceux qui sont engagés dans la viticulture biologique, on trouve la conviction de pouvoir retrouver une plus forte expression des spécificités du terroir dans les vins grâce à l'abandon d'intrants de synthèse (pesticides et fertilisants) (Fassier-Boulanger 2014b; Baudouin 2010).

Enfin un moteur de changement de pratiques est le souci de transmission d'une terre saine aux générations futures (Schott et al. 2004; Jourjon et al. 2014).

Une évolution des choix techniques vers plus de respect de l'environnement est donc bien nécessaire et déjà en marche. Elle demande une prise en compte de l'interconnexion des opérations techniques au sein de l'itinéraire technique. Comme le souligne Walsdorff (2005) de bonnes décisions de management environnemental dans le secteur viticole doivent être basées sur des évaluations fiables. Cette nécessaire évolution demande aussi de cibler l'évaluation, au niveau d'échelle auquel se prennent les décisions techniques.

## 2.4 ITINERAIRES TECHNIQUES VITICOLES ET CHOIX DES TECHNIQUES

Le raisonnement d'une technique agricole, lorsqu'elle nécessite d'être initialement pensée ou modifiée, est un processus complexe, qui se joue à l'échelle individuelle, mais aussi collective par le biais d'échanges d'informations entre agriculteurs et avec les prescripteurs (Compagnone et al. 2008). Ainsi l'adoption de techniques respectueuses de l'environnement préconisées par les prescripteurs s'étend-elle progressivement de proche en proche dans un réseau de dialogue des vignerons les plus connectés aux autres vers ceux plus périphériques de ce réseau (exemple des vignerons de Buxy, (Compagnone et al. 2008))

La chaîne logique et ordonnée d'opérations culturales qui constitue l'itinéraire technique (Sébillotte 1974) est comprise, en viticulture, entre l'après récolte de l'année n-1 et la récolte de l'année n (Del'Homme and Ugaglia 2011). Toutefois, cette définition tirée des cultures annuelles ne concerne que les pratiques annuelles et ne suffit pas pour une culture pérenne telle que la vigne. Il convient d'y ajouter les choix techniques effectués lors des opérations réalisées occasionnellement sur le vignoble et durant les phases non productives de la vigne, à savoir l'inter-culture avant replantation du vignoble, la plantation, les années de mise à fruit, ainsi que l'arrachage. L'établissement de l'itinéraire technique est guidé par les caractéristiques structurelles des exploitations (conformation et localisation du vignoble) et par des objectifs économiques (Guillaumin et al. 2010). Les choix techniques sont aussi un jeu de compromis entre risque concernant la quantité et la qualité de la récolte et les coûts à engager pour le minimiser. Le niveau de valorisation du produit n'est pas neutre dans ce processus puisqu'il conditionne les ressources disponibles pour sa propre production. Il est, par ailleurs, probable que la nature des exploitations (individuelle ou en gérance) joue un rôle non négligeable dans le niveau de prise de risque, et donc la quantité d'intrants consommés.

Guillaumin (2012) constate, dans les vignobles méditerranéens français, que les viticulteurs adoptent de nouvelles techniques culturales plus durables de manière rationnelle à savoir en lien avec la rentabilité voulue et le risque consenti. Enfin des éléments extérieurs à l'exploitation pèsent sur les choix techniques, comme la disponibilité de la main d'œuvre (mécanisation de la vendange par exemple), mais aussi le rapport direct à la clientèle (Guillaumin et al. 2010) et la demande des marchés concernant les choix techniques (Busca et al. 2013).

Le critère majeur de modification de l’itinéraire technique, à l’échelle du millésime, demeure les conditions climatiques, c’est aussi vrai à moyen terme, mais aussi très probablement par le fait du changement climatique déjà amorcé.

Cependant, comme le soulignent Del'Homme et Ugaglia (2011) , l'itinéraire technique viticole est rarement unique pour une exploitation et se décide à l'échelle parcellaire, selon le cépage, les objectifs de production, les caractéristiques pédoclimatiques ou sanitaires de chaque parcelle et chaque année. C'est donc à cette échelle qu'il convient de pouvoir évaluer les impacts environnementaux de techniques et de l'itinéraire technique pour l'intégration de cette dimension dans les processus décisionnels.

## 2.5 L'ACV POUR L'AIDE AU CHOIX DES TECHNIQUES VITICOLES ?

Comme nous l'avons mentionné précédemment, la pensée cycle de vie, qui considère que les impacts environnementaux ne sont pas réduits aux localités ou aux produits simples mais qu'ils sont des conséquences de la conception "cycle de vie" des produits (Pettersen 2007), est celle qui a été privilégiée dans le cadre de l'affichage des performances environnementales des produits auprès des consommateurs dans de nombreux pays. Il semble alors tout à fait cohérent de baser l'évaluation pour l'évolution des systèmes de production sur les mêmes méthodes que celles qui vont servir à afficher leurs performances aux acteurs de l'aval. C'est ce qui a cours dans l'industrie des biens de consommation dans le cadre de l'Ecolabel européen par exemple. En France, les résultats de la phase de constitution des inventaires de cycle de vie pour l'affichage environnemental des productions agricoles ont d'ailleurs fait naître la conscience, dans les secteurs concernés, que l'outil de modélisation des processus de production qu'est l'ACV peut être un puissant outil d'éco-conception des itinéraires techniques agricoles. Les professionnels de la filière viticole la perçoivent, quant à eux, comme un outil complexe mais pertinent pour challenger leurs pratiques et améliorer les performances des entreprises vinicoles (Jourjon et al. 2014). Une des préconisations de la partie consacrée à la filière viticole du rapport prospectif de l'INRA « vers des agricultures à hautes performances » (Coudurier B. et al. 2013) est d'ailleurs intitulée « encourager le recours aux outils d'aide à la décision et analyses du cycle de vie ».

### 2.5.1 LA METHODE ACV

L'ACV est basée en effet sur une modélisation en sous processus, de l'ensemble du processus de production et peut offrir une approche très détaillée des opérations qui le composent. Cela permet d'identifier les points à améliorer et de proposer et tester, à priori, des solutions (Jolliet et al. 2010b). Cette évaluation détaillée de la contribution de chaque étape à l'impact du produit passe par quatre étapes principales décrites dans la norme ISO 14040 (ISO 2006) (Figure 1) :

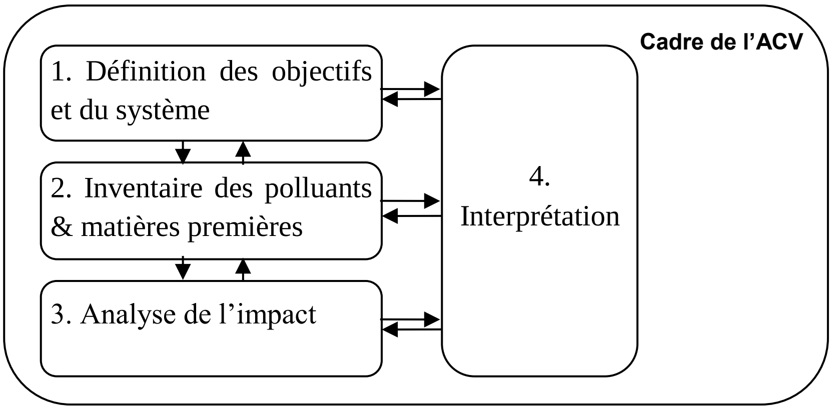


*Figure 1: Les étapes de l'ACV selon la norme ISO 14040 (ISO 2006)*

1) Une définition des objectifs et du champ de l'étude incluant les limites du système étudié, la fonction principale du système à laquelle les impacts seront rapportés (unité fonctionnelle),

ce "service rendu" par le système sera l'entité comparée dans le cas d'ACV comparatives (Guinée et al. 2001)

2) L'établissement des flux d'énergie et de matière entrant et sortant du système étudié, l'inventaire du cycle de vie (ICV) ce qui demande un travail important de collecte de données de terrain et de données secondaires, à ajuster niveau de détail attendu dans les résultats.

3) Ces flux sont ensuite transformés en impacts environnementaux (appelés mid-point) par le biais de facteurs de caractérisation propres à chaque substance, au compartiment (eau air sol) dans lequel elle est rejetée ou prélevée et à chaque catégorie d'impact, c'est la caractérisation ou analyse des impacts du cycle de vie (AICV). Il est aussi possible de calculer des résultats en "dommages" (appelés end-point) occasionnés sur un sujet à protéger. De nombreuses méthodes de caractérisation ont été mises au point et sont disponibles.

4) la dernière étape qui a lieu tout au long des trois premières est l'interprétation. L'ACV est en effet une méthode itérative qui demande parfois plusieurs cycles d'amélioration ou d'approfondissement en fonction des premiers résultats.

L'approche du berceau (extraction des matières premières) à la tombe (fin de vie du produit) caractéristique de l'ACV permet d'identifier d'éventuels transferts d'impacts d'une étape du cycle de vie à l'autre ou d'une catégorie d'impacts à l'autre lors des phases d'amélioration du processus étudié. La pensée cycle de vie amène aussi à envisager les impacts d'un produit plus largement que sur son environnement immédiat, via des catégories d'impact locaux certes, mais aussi régionaux et globaux.

### 2.5.2 L'ACV APPLIQUEE A L'AGRICULTURE ET LA PRODUCTION DE VIN

Conçue à l'origine pour l'industrie et largement adaptée à l'agriculture dans les deux dernières décennies, l'ACV est normalisée (ISO 2006). Il demeure que cette méthode a plutôt été utilisée en agriculture pour la comparaison de systèmes de production (Alaphilippe et al. 2013; Nemecek et al. 2001), la quantification des impacts d'un produit donné (Gazulla et al. 2010), la comparaison de modalités d'une technique prise isolément (Pradel 2013) ou l'affichage environnemental (Colomb et al. 2014) et peu à notre connaissance pour un appui au choix précis des techniques de l'ensemble d'un itinéraire. C'est notamment le cas en viticulture où, parmi la trentaine d'ACV publiées (Petti et al. 2010; Benedetto et al. 2013), l'accent a majoritairement été mis sur l'évaluation du produit final, à savoir une bouteille de vin. Elles englobent alors tout le cycle de vie du produit, au contraire de la plupart des ACV agricoles qui sont le plus souvent réalisées du berceau aux portes de la ferme ou du champ car leur objectif porte sur l'amélioration de la phase de production (Hayashi et al. 2006b). Les ACV dans le domaine du vin ont plutôt eu pour objet la quantification de l'impact global et l'identification des étapes les plus contributives aux impacts dans tout le processus de production de l'échelle d'un vin (Fusi et al. 2014a; Benedetto 2013), pour une exploitation, à une échelle régionale (Vázquez-Rowe et al. 2012a; Neto et al. 2012; Point et al. 2012), voire des comparaisons internationales (Rochat et al. 2009) et des comparaisons de systèmes de production (Villanueva-Rey et al. 2014a). Aucune n'a détaillé l'impact environnemental des techniques viticoles pour raisonner précisément leur choix ou leur évolution à l'échelle parcellaire, bien que certaines de ces études aient identifié la production de raisins dans le système de production. Jusqu'à très récemment (Bellon-Maurel et al. 2014), la majorité des auteurs a proposé peu d'éléments de mise au point de la méthode spécifiques à la viticulture et aucun ne s'est intéressé au croisement avec les objectifs de production et de qualité de produit dans le cadre de productions d'AOC. Pourtant, comme soulignent Marshall et al (2005), des recherches sur la relation entre gain environnemental et gain de qualité du produit sont nécessaires dans la filière vin afin de mieux motiver les producteurs à adopter des techniques plus respectueuses de l'environnement.

## 2.6 LA QUALITE ORGANOLEPTIQUE, CAPITALE EN VITICULTURE AOC…A RELIER A LA PERFORMANCE ENVIRONNEMENTALE

Le terme de qualité d'un produit peut être ambigu du fait des différentes dimensions qu'il recouvre (Hérault-Fournier and Prigent-Simonin 2005; Warner 2007; Charters and Pettigrew 2007). Les dimensions liées à la sécurité alimentaire, la qualité du service, la différenciation culturelle concernent directement la filière vin, toutefois, la dimension organoleptique (intrinsèque) est celle qui, avec la sécurité alimentaire concerne le plus directement l'itinéraire technique viticole. En effet, la qualité de la matière première est essentielle pour la production d'un vin de qualité et l'itinéraire technique en est le déterminant principal avec le milieu (Bravdo 2001a; Conde et al. 2007; Morlat 2010; Coulon 2012).

Le lien unique de la viticulture au terroir (milieu + techniques) et à la qualité organoleptique revêt une importance considérable en Europe et spécifiquement en France du fait de la place que tiennent les productions de vins sous cahier des charges AOC (la moitié du volume produit, et plus de 60% de la surface du vignoble (France-Agrimer 2013)).

Les vins des nouveaux pays producteurs remportent sur les marchés internationaux un succès grandissant depuis environ quinze ans, à l'origine grâce à la simplicité d'approche de leur gamme et de leurs messages commerciaux (Remaud et al. 2010). Plus récemment ils cherchent, par la mise en avant de spécificités géographiques et d'avantages environnementaux, à rejoindre les préoccupations actuelles des consommateurs et des metteurs en marché pour consolider leur position (Remaud et al. 2010; Warner 2007). Les producteurs de vins français dans un contexte de baisse de consommation constante sur le marché domestique (OIV 2013a), doivent sans cesse accroitre leurs exportations tout en faisant face à cette concurrence. La prise en compte des attentes tant qualitatives qu'environnementales des metteurs en marché, notamment sur les marchés d'exportations est donc capitale ; les professionnels de la filière viticole française en ont parfaitement conscience (Jourjon et al. 2014)

La qualité organoleptique est un facteur essentiel de la satisfaction des consommateurs de vins que ces derniers ne sont majoritairement pas prêts à sacrifier au profit des performances environnementales du vin (Lockshin and Corsi 2012; Symoneaux and Jourjon 2013). Ces mêmes auteurs notent que les vins reliés à une indication d'origine disposent d'un capital confiance supérieur concernant leur qualité intrinsèque de la part des consommateurs.

En France, l’AOC ne constitue pas une garantie contre les atteintes à l’environnement du fait de l’absence d’incitation environnementale explicite dans la plupart cahiers des charges de production viticoles (Hirczak 2007). Cependant, les consommateurs de vin français ont plus confiance dans la prise en compte de la protection de l’environnement dans les itinéraires de production des vins d’AOC que des autres vins (Jourjon et al 2014).

Les vignerons des AOC doivent donc, pour conserver ce capital confiance, pour répondre aux attentes institutionnelles et sociétales et pour consolider leur place sur les marchés internationaux, progresser dans les performances environnementales de leurs vins, en préservant la qualité de leurs produits.

# 3 PROBLEMATIQUE ET DEMARCHE

Dans ce contexte, afin d’accompagner la filière viticole française, et en particulier ligérienne d’AOC, vers des choix techniques éco-efficients et vers l’écoconception d’itinéraires techniques, nous avons donc souhaité, dans cette thèse, explorer dans quelle mesure l'ACV peut être une méthode utile et adaptée à l'évaluation et l'amélioration des performances environnementales des itinéraires techniques viticoles à l’échelle parcellaire.

Dans le cadre particulier des vins AOC, l'exigence élevée de qualité organoleptique du produit assortie d'un cadre contraint de conduite technique lié aux cahiers des charges de production donnent une couleur particulière aux décisions techniques. Des choix d'évolution des itinéraires techniques viticoles AOC ne peuvent se faire sans intégrer cette dimension qualitative. Ceci nous amène à assortir notre première question d'une seconde, complémentaire : peut-on intégrer l'objectif qualitatif assigné à un itinéraire technique viticole dans l'évaluation de ses performances environnementales par ACV?

Notre question de recherche est donc la suivante :

**Dans quelles conditions l’ACV est-elle une méthode appropriée à l'évaluation environnementale des itinéraires techniques viticoles de production de raisins de qualité à l’échelle parcellaire à des fins de choix des techniques?**

Pour répondre à cette question de recherche, cinq étapes de travail ont été définies, basées sur le postulat que le vigneron établit son itinéraire technique en interprétant le milieu (sol, climat moyen et annuel) dans lequel sa vigne est implantée:

1) **Choix des cas d'étude** : Afin d'explorer l'intérêt de l'ACV pour l'évaluation et l'amélioration des performances environnementales des itinéraires techniques et des techniques viticoles, en lien avec la qualité du raisin, nous avons souhaité disposer de situations réelles contrastées. Travailler sur des situations de terrain permet en effet de se confronter aux conditions réelles d'acquisition de données et le contraste doit permettre d'identifier si la méthode donne satisfaction dans une diversité de cas. Pour disposer d'itinéraires techniques viticoles contrastés et orientés vers un objectif de produit semblable (vin blanc sec de Chenin AOC de Moyenne Vallée de la Loire), c'est à dire remplissant une

fonction comparable, et issus d'une diversité régionale caractérisée, une méthode spécifique a été mise au point.

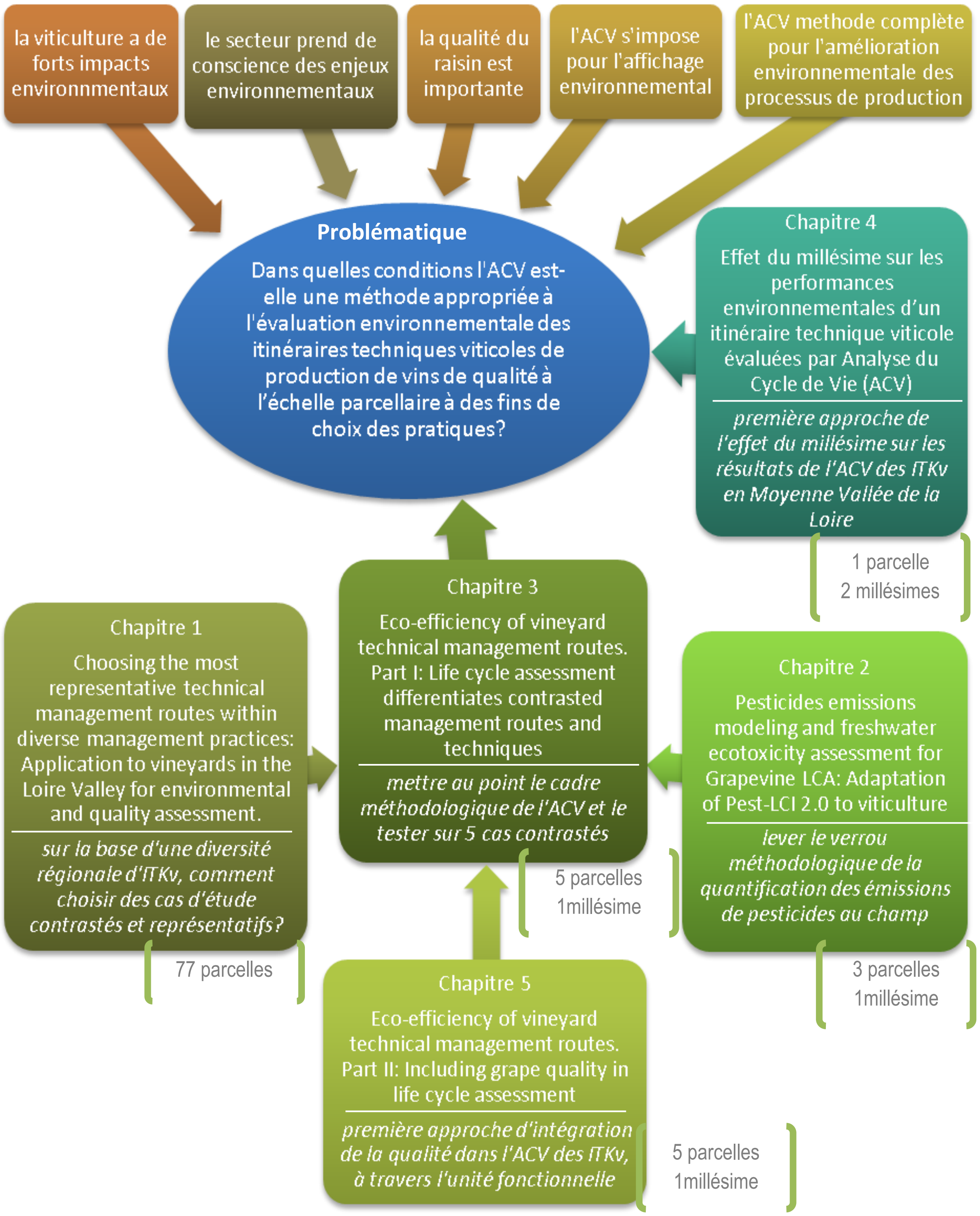
2) **Mise au point du cadre méthodologique pour l'ACV des itinéraires techniques viticoles à l'échelle parcellaire**. L'importance de la consommation de pesticides en viticulture et l'absence de modèle adapté à la viticulture pour la quantification des émissions de pesticides lors de l'application au champ font de ce point un verrou scientifique fort, question que nous avons souhaité tenter de résoudre par une adaptation du modèle actuellement le plus avancé pour cet objectif et conçu initialement pour les grandes cultures. D'autre part, les limites spatiales et temporelles à prendre en compte, et les modèles d'émission des polluants doivent être déterminés.

3) **Mise en œuvre de la méthode d'analyse du cycle de vie sur des itinéraires techniques viticoles. A**fin de vérifier l'adéquation de l'ACV à l'objectif de mesurer et améliorer l'éco-efficience des itinéraires techniques viticoles à l'échelle parcellaire, la méthode sera mise en œuvre sur la base de cas réels contrastés.

4) **Etude de l'effet du millésime sur l'éco-efficience d'un ITK**. La mise en œuvre de l'ACV pour une même parcelle sur deux millésimes climatiquement contrastés vise une quantification de l'ordre de grandeur de la variation potentielle d'éco-efficience entre millésimes dans le contexte ligérien.

5) **Inclusion de la qualité des raisins dans l'ACV** de l'itinéraire technique viticole. Nous avons souhaité tester une première méthode d'inclusion de la qualité du raisin dans l'ACV. Par le biais de l'unité fonctionnelle, la qualité est prise en compte dans le calcul d'éco-efficience de la production de raisin.

Ce manuscrit est donc organisé selon ces cinq objectifs (Figure 2). Il repose sur cinq articles scientifiques (un par chapitre) dont un accepté dans European Journal of Agronomy (Chapitre1), un soumis et en révision dans International Journal of Life Cycle Assessment (chapitre 2), et trois articles (chapitres 3, 4 et 5) en préparation pour soumission à une revue scientifique (dont un a été présenté en tant qu'article de congrès au congrès OIV2014, Chapitre 4).



la viticulture a de forts impacts environnmentaux

le secteur prend de conscience des enjeux environnementaux

la qualité du raisin est importante

l'ACV s'impose pour l'affichage environnemental

l'ACV methode complète pour l'amélioration environnementale des processus de production

**Problématique**

Dans quelles conditions l'ACV est-elle une méthode appropriée à l'évaluation environnementale des itinéraires techniques viticoles de production de vins de qualité à l'échelle parcellaire à des fins de choix des pratiques?

Chapitre 4

Effet du millésime sur les performances environnementales d'un itinéraire technique viticole évaluées par Analyse du Cycle de Vie (ACV)

*première approche de l'effet du millésime sur les résultats de l'ACV des ITKv en Moyenne Vallée de la Loire*

1 parcelle
2 millésimes

Chapitre 3

Eco-efficiency of vineyard technical management routes. Part I: Life cycle assessment differentiates contrasted management routes and techniques

*mettre au point le cadre méthodologique de l'ACV et le tester sur 5 cas contrastés*

5 parcelles
1millésime

Chapitre 1

Choosing the most representative technical management routes within diverse management practices: Application to vineyards in the Loire Valley for environmental and quality assessment.

*sur la base d'une diversité régionale d'ITKv, comment choisir des cas d'étude contrastés et représentatifs?*

77 parcelles

Chapitre 2

Pesticides emissions modeling and freshwater ecotoxicity assessment for Grapevine LCA: Adaptation of Pest-LCI 2.0 to viticulture

*lever le verrou méthodologique de la quantification des émissions de pesticides au champ*

3 parcelles
1millésime

Chapitre 5

Eco-efficiency of vineyard technical management routes. Part II: Including grape quality in life cycle assessment

*première approche d'intégration de la qualité dans l'ACV des ITKv, à travers l'unité fonctionnelle*

5 parcelles
1millésime

*Figure 2 : problématique de la thèse, démarche et structure du manuscrit*

La zone d'étude sélectionnée pour ces travaux est la Moyenne Vallée de la Loire, plus précisément les AOC Anjou Blanc, Saumur Blanc et Savennières (Figure 3).

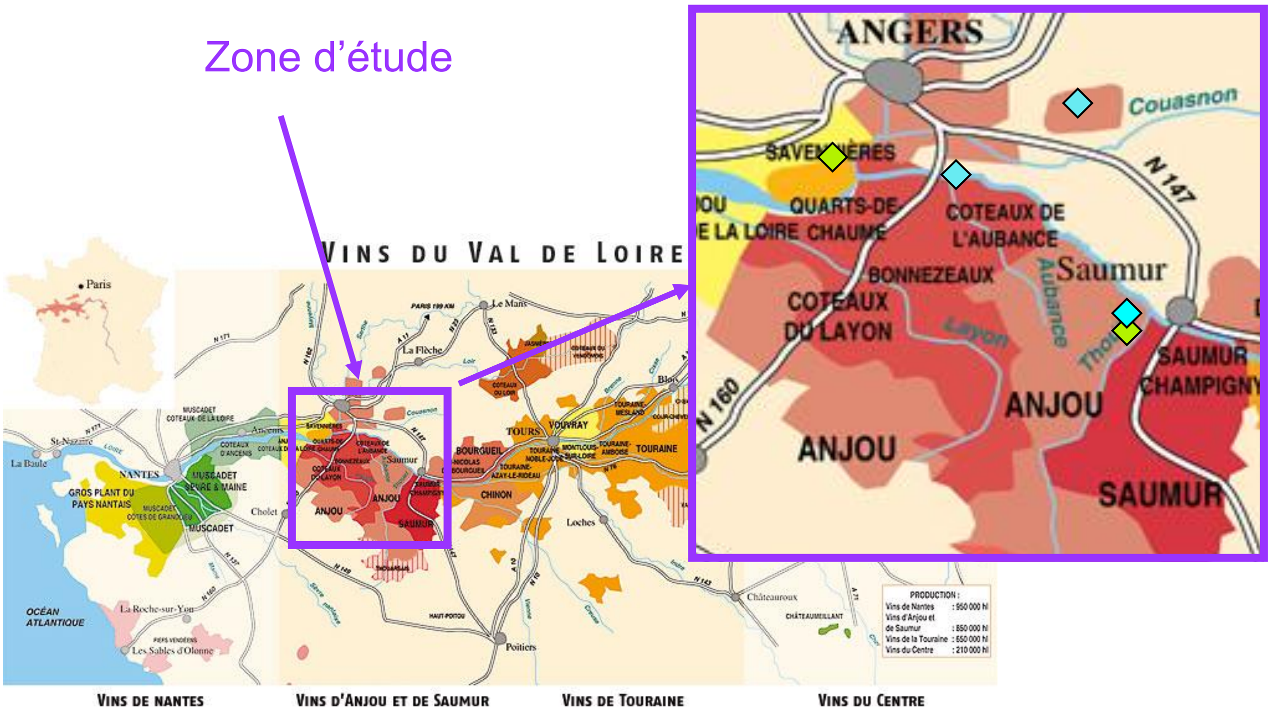


Figure 3: Localisation de la zone d'étude (AOC Saumur Banc, Anjou Blanc et Savennières, en moyenne Vallée de la Loire (France) (source fond de carte Vins du Val de Loire) et des parcelles sélectionnées losanges verts, parcelles en agriculture biologique, en bleu raisonné ou conventionnel

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# CHAPITRE 2

# CHOOSING THE MOST REPRESENTATIVE TECHNICAL MANAGEMENT ROUTES WITHIN DIVERSE MANAGEMENT PRACTICES: APPLICATION TO VINEYARDS IN THE LOIRE VALLEY FOR ENVIRONMENTAL AND QUALITY ASSESSMENT

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## KEYWORDS

Cropping systems, partitioning, association rules, typology, viticulture, Life Cycle Assessment

## ABSTRACT

Diversity of agricultural systems can be described at different scales in terms of three main types of variables: technical management of cropping systems, farming systems and food supply chains. We focus on the diversity of technical management routes (TMRs), defined as logical successions of technical options (TOs) designed by the farmers. The study, comparison and assessment of this great diversity of complex routes are impossible with classical agronomic experiments or exhaustive assessments such as Life Cycle Assessment (LCA). Hence, the selection of representative cases is necessary. Multidimensional data analysis methods permit the characterization of a diversity of TMRs and the construction of typologies but do not allow the consideration of the specific associations of TOs constituting the various TMRs.

The aim of this paper is threefold: i) to propose a new combined method, “Typ-iti”, to classify the field TMRs of farmers, to identify key TO associations and to select the most relevant cases for study; ii) to test this method on vineyard management diversity using a panel of vineyard fields of Loire Valley producers; and iii) to discuss the capability of the proposed Typ-iti method for use in the characterization and selection of cases of other agricultural systems at diverse scales.

The example developed in this paper is the selection of vineyard management cases for grape LCA combined with grape quality evaluation. The cases were selected to represent the regional diversity of management practices. A detailed on-farm survey of management methods was performed on a diverse range of wine production estates in the Middle Loire Valley. The Typ-iti method was constructed and implemented on the survey database. It combines a multidimensional analysis of qualitative survey data and typology and partitioning (clustering) associated with data mining methods (frequent pattern mining search and association rules).

The surveyed sample was partitioned into 5 types of management practices, 2 of which were organic and 3 conventional. The partitioning was driven primarily by choices involving pest management and floor management. Each type was characterized by specific TOs, specific associations of TOs and remarkable TMRs. The cases were chosen on the basis of these 3 parameters.

The Typ-iti method can be applied to other crops and at different scales; the only limitation is the availability of precise information on the practices used by farmers in their fields.

# 1 INTRODUCTION

Coping with cropping system technical management (CSTM) is essential for studying and assessing agricultural systems diversity. CSTM is, indeed, a central issue for agronomists (Benoît et al. 2012). This topic is challenging because it requires descriptions of CSTM and modeling of the resulting impacts. This topic is one of the most productive in the literature of agronomy for both annual crops (Andrianasolo et al. 2014; Colbach et al. 2014; Franzluebbers and Stuedemann 2013) and perennial crops (Monteiro and Sentelhas 2013; Liu et al. 2014). The level of analysis involved in such research is shifting from plots (Andrianasolo et al. 2014) to watersheds (Amon-Armah et al. 2013) or entire countries (Xiao and Tao 2014). To optimize agricultural production, the technical management pursued by each farmer consists of choosing and associating technical options (TOs) in a chosen manner throughout the production season and, for perennial crops, for more than a season. Each farmer makes these choices relative to not only economic, qualitative, environmental or work organization constraints but also an overall work philosophy. As previously shown by a number of agronomic studies, TOs are not "spread" over time but are linked and ordered by farmers through a mental logical framework (Debaeke et al. 2009; Le Gal et al. 2011; Papy 2008; Sébillotte 1974; Loyce et al. 2002; Sébillotte 1990). We will call this ordered chain of TOs a technical management route (TMR) according to the definition presented by (Sébillotte 1974). Knowledge of this pattern of field management is a challenge for agronomists involved in the field of Land Change Science (Rounsevell et al. 2012). Assessing and comparing these agricultural TMRs, e.g., to select the optimal one, is a problem in classical agronomic experiments (Debaeke et al. 2009) due to the immense number of possible combinations, especially for perennial species (Coulon-Leroy et al. 2013). Environmental impact assessment of TMRs through Life Cycle Assessment (LCA) (ISO 2006) is another situation in which the choice of a limited number of TMRs must be made on the basis of a complex and time-consuming assessment (Pradeleix et al. 2012). Indeed, the time-consuming data collection and calculation required for agricultural LCA imply that a limited number of cases that are often not statistically representative may appear in LCA studies (Dalgaard et al. 2006). Moreover, the extrapolation of crop production inventories is problematic due to the substantial variation in production conditions (Nemecek and kägi 2008). For this reason, there is a need for a rigorous selection of typical cases to ensure the use of representative data for LCA and to identify the limits of extrapolation of the results. A small number of combinations must be chosen, either representative of the existing diversity or contrasted, according to the aim of the study.

Analyzing the diversity of TMRs existing in a given area through a typology allows i) the description of the diversity of TO combinations; ii) the choice of representative cases within this diversity; iii) the assessment of the representativeness or contrasting properties of previously selected cases (obtained in an experiment, for example); and iv) the selection of groups of TMRs for comparative analyses.

Several typologies for agricultural TMRs can be found in the literature on apple orchards, banana crops and sheep farm management (Nesme et al. 2003; Bellon et al. 2001a; Girard et al. 2001; Blazy et al. 2009; Bellon et al. 2001b), but the classical data analysis methods used do not permit the identification of logical associations between TOs in terms of TMRs.

As the farmer uses a mental logical framework to determine the choice of TOs for the TMR, the process of selecting cases is improved by identifying the options that are always combined in particular types of TMRs. To our knowledge, studies of the combination of TOs are extremely limited, especially in viticulture (Scholtus-Thiollet et al. 2008; Coll 2011) and have never been joined to typologies. Accordingly, the aim of this paper is i) to propose a generic method for selecting the most representative cases for study within an existing diversity of TMRs while considering the TO associations made by the producers and ii) to assess the use of the method for vineyard management. The method combines a typology based on a multidimensional analysis results, which is used to obtain distinct families of TMRs, and then the use of data mining methods (association rules) to identify the TO associations characteristic of each TMR family. In this paper, the method is described in terms of its application to the diversity of crop management and is illustrated by an application to vineyard management. The choice of vineyards to study diversity is based on the substantial level of variability in the factors that drive CSTM choices by farmers. In the vineyard example, the probability of identifying diverse management approaches is high because of the diversity of soil quality, the types of wine that are produced and the 2 spheres of management, i.e., of the vegetation and of the soil. Furthermore, grape production implies TMRs that include numerous steps and a wide range of TOs available for each TMR step, especially if the full diversity of growing systems (conventional, integrated, organic and biodynamic) is considered. Hence, the combinations of available TOs can generate an immense number of TMRs (Scholtus-Thiollet et al. 2008). However, we chose to develop a generic method that could readily be adapted for other crop management studies.

The method and the selected case presented in the paper were developed as a first step in the framework of a project aiming to assess viticulture TMRs in terms of their effects on quality and environmental performances assessed using LCA (Renaud et al. 2011).

In this paper, we successively present i) the material used, a set of on-farm surveys addressing farmers' practices in their fields, and the method, an original sequence of statistical analyses; ii) the framework of this data mining method; (iii) the main results obtained from the viticulture case study; and iv) the advantages, limitations and perspectives of this method for modeling the diversity of combinations of TOs, followed by some concluding points.

# 2 MATERIALS AND METHODS

In this section, we describe the sequence of methods used to characterize the TMRs and select the most relevant cases. After presenting the definitions of key terms, this section describes general procedures, the construction of the TMR database, the use of clustering methods to group TMRs, the analysis of the characteristic TOs that are linked to each cluster and the process of case selection. Finally, we present the sample of viticulture data to which the method was applied.

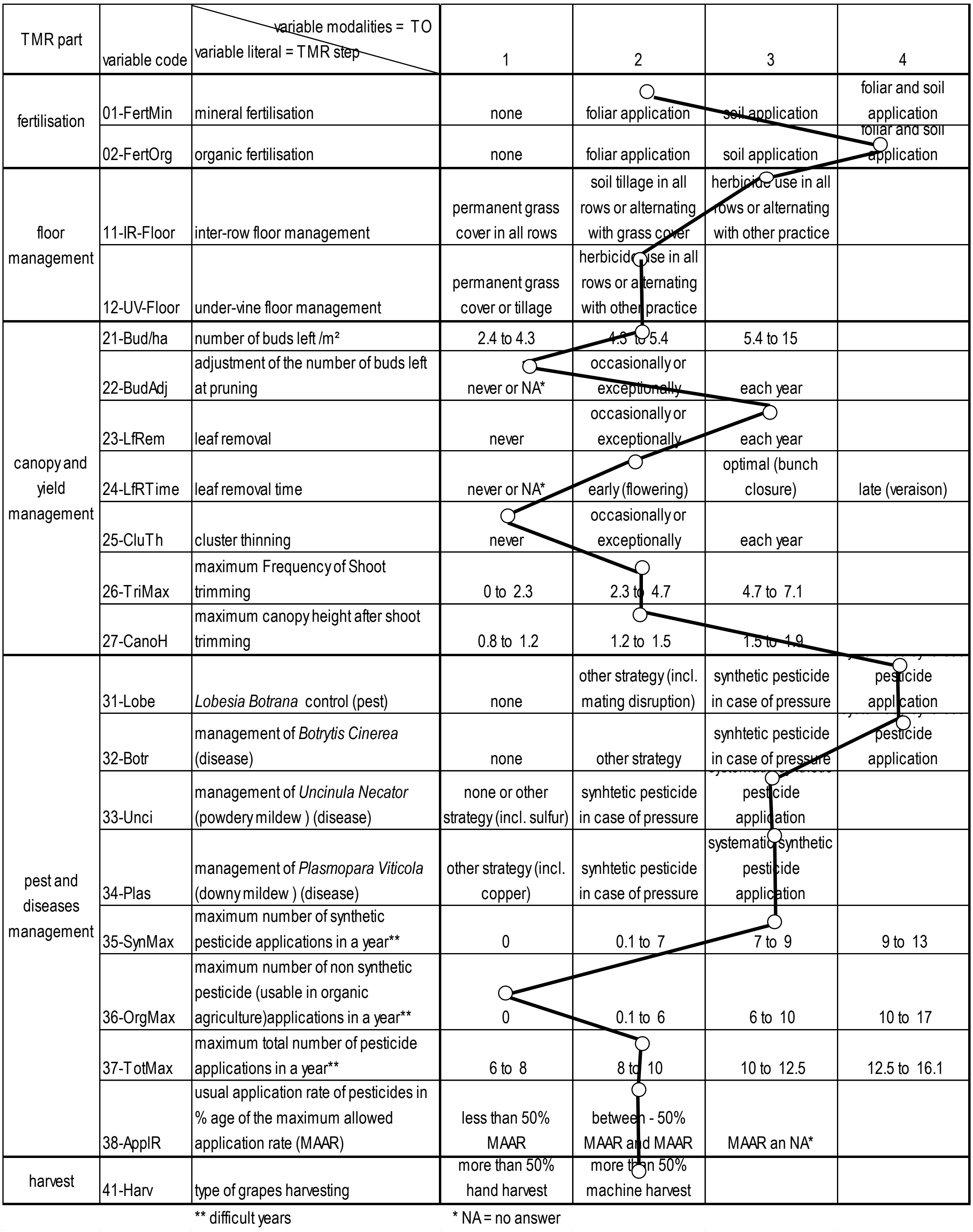
## 2.1 DEFINITIONS

The key terms used for TMR description are defined in Table 1, and an example of the viticultural TMR of one parcel from the sample produced by the surveys is presented in Table 1.

*Table 1: Definitions and acronyms for the concepts used for TMR description*

| Concept and acronym | definition | examples in the vineyard |
|---|---|---|
| Technical option (TO) | an action or a number of similar actions performed or executed in the field by the farmer | "no mineral fertilisation", "early leaf removal", "high total number of synthetic treatments per year" or "uncinula necator management by sulfur" |
| Technical management route (TMR) | According to (Sébillotte, 1974), a technical management route in agriculture is a logical and ordered combination of agricultural TO. | see the viticultural TMR of one parcel from the surveyed sample in Table 2 |
| TMR step | A TMR step is defined here as a unit of the TMR which modalities are the possible TO the farmer can choose to implement at this step. | In Table 2, for the TMR step "mineral fertilisation", the farmer can choose the following TO: "none", "foliar application", "soil application", "foliar and soil application". |
| TMR part | In order to classify the TMR steps, they were grouped into distinct TMR parts according to the different elements of the system that are targeted (for vineyard: plant, soil, canopy, pest and disease, fruits). They, at the same time, involve different equipment and inputs | see the viticultural TMR parts in the 1rst column in Table 2 |

*Table 2: Example of a TMR (from a parcel obtained by the surveys of viticulture)*



| TMR part | variable code | variable modalities = TO<br>variable literal = TMR step | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|
| fertilisation | 01-FertMin | mineral fertilisation | none | foliar application | soil application | foliar and soil application |
| | 02-FertOrg | organic fertilisation | none | foliar application | soil application | foliar and soil application |
| floor management | 11-IR-Floor | inter-row floor management | permanent grass cover in all rows | soil tillage in all rows or alternating with grass cover | herbicide use in all rows or alternating with other practice | |
| | 12-UV-Floor | under-vine floor management | permanent grass cover or tillage | herbicide use in all rows or alternating with other practice | | |
| canopy and yield management | 21-Bud/ha | number of buds left /m² | 2.4 to 4.3 | 4.3 to 5.4 | 5.4 to 15 | |
| | 22-BudAdj | adjustment of the number of buds left at pruning | never or NA* | occasionally or exceptionally | each year | |
| | 23-LfRem | leaf removal | never | occasionally or exceptionally | each year | |
| | 24-LfRTime | leaf removal time | never or NA* | early (flowering) | optimal (bunch closure) | late (veraison) |
| | 25-CluTh | cluster thinning | never | occasionally or exceptionally | each year | |
| | 26-TriMax | maximum Frequency of Shoot trimming | 0 to 2.3 | 2.3 to 4.7 | 4.7 to 7.1 | |
| | 27-CanoH | maximum canopy height after shoot trimming | 0.8 to 1.2 | 1.2 to 1.5 | 1.5 to 1.9 | |
| pest and diseases management | 31-Lobe | *Lobesia Botrana* control (pest) | none | other strategy (incl. mating disruption) | synthetic pesticide in case of pressure | pesticide application |
| | 32-Botr | management of *Botrytis Cinerea* (disease) | none | other strategy | synhtetic pesticide in case of pressure | pesticide application |
| | 33-Unci | management of *Uncinula Necator* (powdery mildew ) (disease) | none or other strategy (incl. sulfur) | synhtetic pesticide in case of pressure | pesticide application | |
| | 34-Plas | management of *Plasmopara Viticola* (downy mildew ) (disease) | other strategy (incl. copper) | synhtetic pesticide in case of pressure | systematic synthetic pesticide application | |
| | 35-SynMax | maximum number of synthetic pesticide applications in a year** | 0 | 0.1 to 7 | 7 to 9 | 9 to 13 |
| | 36-OrgMax | maximum number of non synthetic pesticide (usable in organic agriculture)applications in a year** | 0 | 0.1 to 6 | 6 to 10 | 10 to 17 |
| | 37-TotMax | maximum total number of pesticide applications in a year** | 6 to 8 | 8 to 10 | 10 to 12.5 | 12.5 to 16.1 |
| | 38-ApplR | usual application rate of pesticides in % age of the maximum allowed application rate (MAAR) | less than 50% MAAR | between - 50% MAAR and MAAR | MAAR an NA* | |
| harvest | 41-Harv | type of grapes harvesting | more than 50% hand harvest | more than 50% machine harvest | | |

** difficult years * NA = no answer

## 2.2 THE GENERAL PROCEDURE FOR THE TYP-ITI METHOD

The Typ-iti method consists of a sequence of three main operations, as presented in the rectangles with rounded corners in Figure 4. The “association rules” method is described in §2.4.4. The construction of a database describing a sample of TMRs obtained through an on-farm survey can be replaced by the use of existing databases.

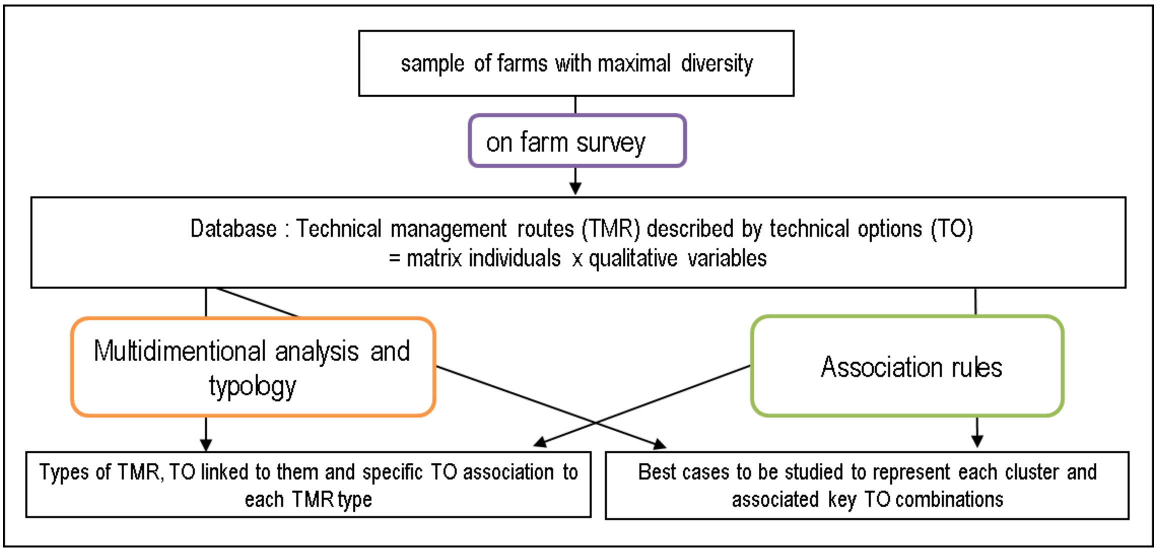


*Figure 4: The general procedure for the Typ-iti method*

## 2.3 THE TYP-ITI METHOD: THE STAGE OF TMR DATABASE CONSTRUCTION

### 2.3.1 SURVEY SAMPLE AND QUESTIONS

To represent the TMR diversity of a given area, it was hypothesized that a great diversity of socio-economic situations would maximize the diversity of field management strategies in the sample. Consequently, the farms were chosen to obtain a wide range of variation in the most significant criteria (Figure 5), namely, the estate size; the type of growing system (conventional, integrated, organic or biodynamic); and the type of trade (e.g., through a cooperative, direct sales). See the viticulture example in §2.5.2 for additional criteria. The criteria have been adjusted to reflect to the area and the crop.

The survey was conducted at the parcel scale. A parcel is defined here as a consistent crop cover (annual or perennial) with a common farmer, crop variety, age of plants and TMR.

A list of the steps constituting a TMR and their possible modalities (TOs) was established. Based on this list, the most significant TMR steps were selected for data treatment according to the process described in §2.3.4.

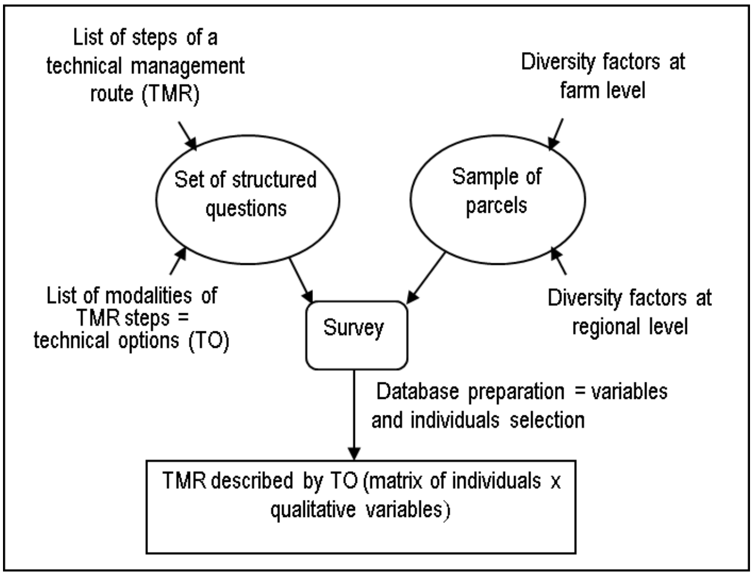


*Figure 5: Process for the construction of a database of vineyard TMRs for Chenin Blanc in the Middle Loire Valley.*

## 2.3.2 VARIABLES AND DATA MANAGEMENT

### Software

QuestionData software, version 6.7 (Grimmersoft 2008) was used for questionnaire management, response input, variable transformations and complete database management.

### Database preparation

A reduced database was built from the survey database. The reduced database included the variables describing the TOs selected for data treatment. A question in the survey such as “what is the maximum number of times/year you trim the shoots in the vineyard in humid years?” corresponds to a TMR step and generates a variable such as “maximum frequency of shoot trimming”. The answers to the question correspond to the possible technical choices made by the winegrower, i.e., the TOs, and they generate the variable modalities. The quantitative variables were transformed into categorical variables by partitioning their values into 2 to 4 classes, and several of the modalities for the categorical variables were merged to avoid obtaining an unacceptably small modality sample size. Certain variables were created by performing calculations on the original data, followed by transformation into categorical variables.

The selection process for the variables included the verification of their power to perform discriminations.

### Selection of variables

The process of selection was as follows. The TMR steps for which more than 75% of the individuals practiced the same TO were not included because, in this case, the variables did not discriminate between distinct situations. Moreover, certain variables that provided redundant information or would place excessive weight on certain topics were eliminated.

### Selection of individuals (= TMRs)

A correlation matrix representing all the surveyed TMRs on the basis of the selected variables permitted the elimination of redundant TMRs. A correlation coefficient of 0.975 was used to define 2 TMRs as similar.

## 2.4 THE TYP-ITI METHOD: DATA ANALYSIS STAGE

All of the steps of the data analysis stage of the Typ-iti method are described in Figure 6, beginning from a matrix of TMRs described by qualitative variable modalities corresponding to TOs. On the left-hand side of the chart, the multidimensional and clustering methods serve to define the clusters; on the right-hand side, the association rules offer complementary information about the logic of combinations between TOs and the most frequent, specific and even exclusive combinations of TOs for each cluster. The Typ-iti procedure yields information on i) the types of TMRs and their description in terms of the key TO and the specific TO associations as well as ii) all of the elements useful in choosing TMRs for case studies within the surveyed sample or outside of it.

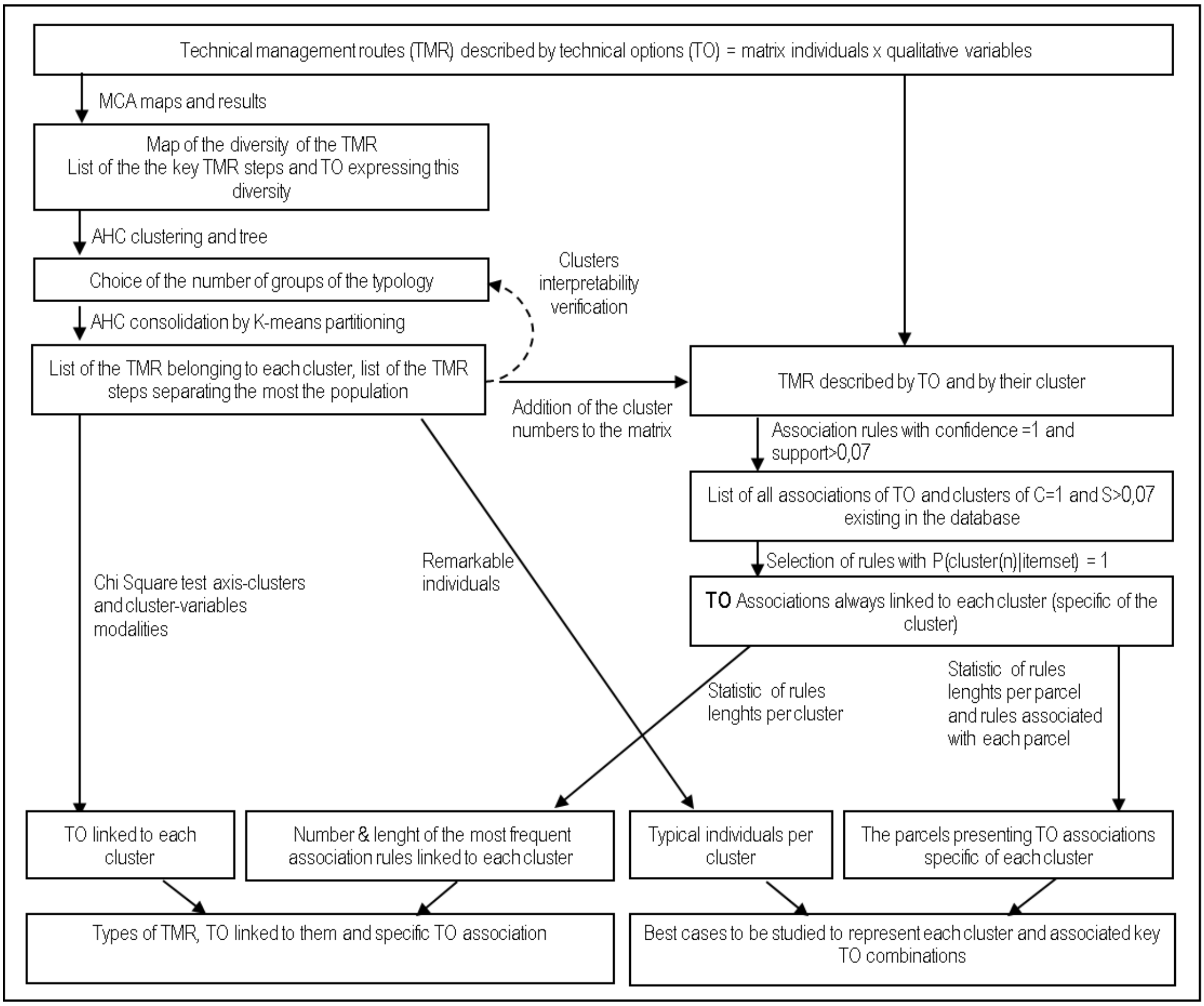


*Figure 6 The Typ-iti method, data analysis stage: the process of selection of the cases and definition of the TMR types and corresponding methods*

### 2.4.1 DATA ANALYSIS TOOLS

Data analysis was performed with R software (R-Development-Core-Team 2007) using different packages, namely, FactoMineR (Husson et al. 2012), ca (Nenadic and Greenacre 2007) and arules (Hahsler et al. 2005).

### 2.4.2 MULTIPLE CORRESPONDENCE ANALYSIS (MCA)

MCA is an exploratory data analysis method for categorical variable description and visualization. A dataset of I individuals and K variables is represented as a cloud of individuals in a low-dimensional Euclidean subspace using a number smaller than K of uncorrelated variables called principal components (Husson et al. 2010). After visualization and description of the diversity of the TMRs, MCA is used here as a pre-processing step before hierarchical and partitional clustering. The analysis is performed on the disjunctive matrix.

### 2.4.3 CLUSTERING

In this study, clustering consists of grouping a set of TMRs into disjoint clusters. One way to verify the quality of a clustering result is to observe the inertia within and among the groups. The inertia within the groups should be minimal, thereby signifying that the individuals are close to each other; the inertia between the groups should be maximal to ensure that the groups differ from each other.

#### Ascendant hierarchical clustering (AHC)

The Ward method of AHC (Wishart 1969; Ward 1963) builds a hierarchical tree through an aggregation of clusters, thereby minimizing the inertia within the clusters. An AHC was performed on the first 4 principal components of the MCA to preserve the principal information and eliminate “noise” to make the clustering more robust (Husson et al. 2010). The number of components was chosen on the basis of their adjusted inertia (Nenadic and Greenacre 2007) (see the vineyard example in Figure 8, chapter 3.2.1) given that after the 4th component, the gain in inertia was too small.

The choice of the number of clusters for the partition was made relative to the general shape of the tree, the gain of inertia between the clusters when adding a cluster and the interpretability of the clusters.

#### K-means partitioning

The K-means algorithm (KM) is an iterative partitional clustering method based on Euclidean distance and used in many applications. MCA, the Ward method of AHC and KM methods use Euclidean distances and can, therefore, be combined (Husson et al. 2010). An AHC typology can be improved by implementing a KM partitioning in its results as proposed by Husson et al.,(2012) in the HCPC function of the R package FactoMineR. The initial partition introduced in the KM is the one obtained from the cut of the AHC tree, and several KM iterations are then performed. The effect of this consolidation can be evaluated by the [(between inertia)/(total inertia)] ratio (Husson et al. 2010); the clusters are represented on the factorial map of the MCA. This treatment was performed on the results of the MCA.

#### Characterization of the clusters by classical methods

The clusters were characterized with 4 complementary indicators, of which 3 represent classical methods: correlation between clusters and modalities of variables by chi² calculation, correlation between axes and clusters and observation of remarkable individuals in KM clusters (paragons and specific individuals). The paragons are the closest individuals from the centroid of the cluster, and the specific individuals are those located farthest from the centroids of the other clusters (Husson et al. 2010). These cases were identified by implementing hierarchical clustering on principal components (HCPC). The fourth method, association rules, is derived from data mining.

### 2.4.4 CHARACTERIZATION OF THE CLUSTERS BY ASSOCIATION RULES

Frequent pattern mining searches are useful to identify relationships in a given dataset. This procedure leads to the discovery of associations and correlations in a large relational dataset. These patterns can be used to identify association rules. Identifying these rules is a powerful tool that was used originally for consumer basket analyses but has also been used recently in agriculture to identify relationships between land use and quantitative measurements (You et al. 2011; Ekasingh and Ngamsomsuke 2009; Xue et al. 2010).

#### a) Association rules between TO chains and the clusters

Association rules between variable modalities (=TOs) and the clusters obtained from hierarchical clustering and K-means partitioning were obtained using the “apriori” algorithm developed by (Agrawal et al. 1993) and implemented by (Borgelt 2003) in the “arules” package (Hahsler and Hornik 2007) in the R statistical environment. The table containing the TMR data was transformed into a matrix in which each variable modality (TO) was described as present (1) or absent (0) for each individual (TMR).

#### Item, itemset and support

An itemset is defined as a group containing 1 or more items (=TOs) and belonging to a TMR. Let us consider A to be an itemset containing k items, with $k \geq 0$. The occurrence frequency of A is the number of TMRs containing A; it is known as the support of an itemset. Let B be another itemset. An association rule is an implication of the form $A \Rightarrow B$, where $A \neq \emptyset$, $B \neq \emptyset$ and $A \cap B \neq \emptyset$. The support of $A \Rightarrow B$ is the percentage of TMRs that contain $A \cup B$.

$$\text{Support}(A \Rightarrow B) = P(A \cup B)$$

An itemset or a rule is frequent if its support is higher than a minimum threshold fixed by the user.

### Confidence

The confidence of the rule A => B is the percentage of TMRs containing A that also contain B. This value is the conditional probability P(B | A).

$$\text{Confidence } (A \Rightarrow B) = P(B \mid A)$$

Rules that satisfy both the minimum support threshold and a minimum confidence threshold are called strong. In this paper, analyses were only conducted with confidence = 1. Thus, if B is an itemset of length 1 containing the class n of a given cluster Cn to which a parcel belongs and A is an itemset of the combination of k-modalities, then A is an exclusive characteristic of the cluster Cn. Thus, each analyzed rule shows the following pattern:

$$\{\text{item1, item2, … itemn}\} \Rightarrow \{\text{Cn=1 to 5}\}$$

The n items on the left-hand side of the rule correspond to the modality of n variables, whereas the right-hand side corresponds to the cluster. The probability with which cluster Cn appears if having A is 1.

The minimal support for the analyzed rules was set to 0.07 to permit the identification of groups of a minimum of 5 TMRs sharing the same rule. This threshold could have been set lower, but the number of rules would then have increased dramatically.

### Adjusted support

To select the most interesting rules (i.e., the rules shared by the greatest number of TMRs in a cluster), we created an “adjusted support” to analyze the rules per cluster: the effective support of the rules was adjusted to the number of TMRs contained in each cluster.

Adj.support = support * total number of TMRs / number of TMRs of cluster Cn. The rules having an adj.support > 0.5 were then analyzed to study rules shared by at least 50% of the TMRs of the cluster. The number of associated rules and the maximum rule length and its support were also determined for each TMR.

### Lift

A simple correlation measure, the lift, was used to test the dependency of two itemsets.

$$\text{Lift } (A,B) = P(A \cup B)/ P(A)P(B)$$

If the value of the lift is less than 1, then the occurrence of A is negatively correlated with the occurrence of B. If the value is greater than 1, A and B are positively correlated. A value of 1 indicates that A and B are independent.

### 2.4.5 IDENTIFICATION OF THE BEST PARCELS FOR A CASE STUDY

In the present project, we need to study the cases that best represent each type of TMR and that are the most contrasting. To identify the best TMR for a case study, the list and map of remarkable individuals, i.e., paragons and specific individuals, were used. A TMR that is simultaneously a paragon and a specific is ideal for a case study for our purposes, but it does not exist in all clusters. The choice is substantially improved by looking for the most frequent associations of TOs identified for each cluster, in the TMRs of the remarkable individuals.

#### a) Identification of the TMR presenting the specific TO associations of each cluster

We identified in the disjunctive matrix, for each cluster, the parcel with the most representative TO associations (the longest rules with highest adj.support and adj.support>0.5). This procedure served as a complementary aid in the choice of the cases for study within the survey sample; before choosing a paragon or a specific individual, we determined whether it presented the TO associations specific to the cluster.

#### Choice of TMRs from the survey sample

When TMRs need to be selected from the survey sample, the selected TMRs can adequately represent the clusters due to the information provided jointly by the association rules and K-means. The researcher will know the most typical TOs of the cluster based on chi² tests between the clusters and the variable modalities. The procedure is completed based on association rules and the example furnished by the paragon TMR.

#### Choice of TMRs from outside the survey sample

In a situation in which it is impossible to select a parcel from the original sample, the new parcel should be characterized by an association of TOs that is as close as possible to the 1st paragon and that includes the most characteristic rules of the cluster.

## 2.5 APPLICATION OF THE TYP-ITI PROCEDURE TO A REAL DATASET

### 2.5.1 CHARACTERISTICS OF THE STUDY SITE

The Typ-iti method was applied to a real dataset for winegrower vineyard TMRs: Middle Loire Valley Chenin Blanc, grown for dry wines.

The Middle Loire Valley (France) offers favorable conditions for growing different vine (*Vitis vinifera*) cultivars and for producing a wide range of wine types (Goulet and Morlat 2011). More than 50 different wine Protected Denominations of Origin (PDOs) can be found in three main production zones, namely, the Anjou, Saumur and Touraine vineyards. The Anjou vineyard soils and subsoils are primarily from schist and metamorphic sandstone of the Armorican Massif, whereas the Saumur and Touraine vineyards are located on the sedimentary marl, chalk and calcareous sands of the Parisian Basin (Goulet and Morlat 2011). In the climatic classification system for grape-growing regions worldwide established by (Tonietto and Carbonneau 2004), the Middle Loire Valley climate was classified as cool and sub-humid during the vegetation period, with very cool nights during the grape maturation period. However, (Barbeau 2007) has reported that the climate became milder and dryer during the 1977-2006 period. Chenin Blanc is the principal white cultivar grown in the Middle Loire Valley, with more than 8300 ha of cultivation and representing 27% of the vineyards of the area (France-Agrimer 2010). Chenin Blanc is very typical of this region, and 85% of French Chenin Blanc is grown in the Middle Loire Valley (France-Agrimer 2010). Chenin Blanc produces dessert-style sweet, dry and sparkling white wines. This study is focused on vineyard TMRs designed for PDO dry wine production from this cultivar. Each PDO set of rules defines a number of fixed practices, such as the type of pruning, number of buds and width of the rows. The PDOs represented in the survey are Anjou Blanc, Chinon Blanc, Saumur Blanc, Savennières and Vouvray.

### 2.5.2 SURVEY SAMPLE AND QUESTIONNAIRE

In May 2010, a detailed survey of 54 winegrowers was conducted regarding the viticultural TMRs of 77 parcels of *Chenin Blanc* grown for dry PDO white wines. The winegrowers were selected to obtain a wide range of variation in the following criteria (figure 2): (i) estate size; (ii) type of growing system (conventional, integrated, organic or biodynamic); (iii) juridical category of the farm; (iv) type of trade (through a cooperative, to a wine merchant, traditional market or direct sale); (v) degree of specialization of the viticulture of the farm; and (vi) prestige and average price of the wines of the PDO. This sample was constructed from official lists of winegrowers (such as regional wine fair exhibitor directories, PDO websites, lists of organic winegrowers and lists of cooperative members).

A parcel was defined as a consistent surface of vineyard with a common grower, cultivar, rootstock, set of vine ages and set of practices. The list of the steps constituting a TMR and their possible modalities (TOs) was established on the basis of our experience of the regional vineyard TOs and discussions with experts. Based on this list, 28 TMR steps were identified, of which 20 were selected for data treatment according to the process described in §3.1. Only annual TMR steps were considered in this study; perennial tasks, such as the density of the plantation, the rootstock, the clone of Chenin Blanc and the height of the perennial part of the vine, were considered elements of context similar to average climate and soil conditions. A set of 98 closed questions about these TMR steps, the parcel context (e.g., the sensitivity of the parcel to disease and frost) and the structure, size and organization of the farm constituted the questionnaire. After a test on 7 winegrowers, the questionnaire was submitted to the winegrowers through a face-to-face interview at his/her farm (Figure 5) by trained undergraduates specializing in viticulture. The discussions were recorded to permit verification of the answers.

# 3 RESULTS: APPLICATION OF THE TYP-ITI PROCEDURE TO A REAL DATASET

## 3.1 VARIABLE SELECTION

Table 3 presents the list of the 20 selected variables, ordered by TMR parts, and their modalities.

*Table 3: Selected variables to describe the surveyed vineyard TMRs, structured in 5 parts: 0) fertilization, 1) floor management, 2) canopy and yield management, 3) pest and disease management and 4) harvest*

| | variable code | variable literal = TMR step | variable modalities = technical options (TO) | | | |
|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 |
| *0)* | 01-FertMin | mineral fertilization | none | foliar application | soil application | foliar and soil application |
| | 02-FertOrg | organic fertilization | none | foliar application | soil application | foliar and soil application |
| *1)* | 11-IR-Floor | inter-row floor management | permanent grass cover in all rows | tillage in all rows or alternating with grass cover | herbicide in all rows or alternating with other technique | |
| | 12-UV-Floor | under-vine floor management | permanent grass cover or tillage | herbicide in all rows or alternating with other technique | | |
| *2)* | 21-Bud/ha | number of buds left /m² | 2.4 to 4.3 | 4.3 to 5.4 | 5.4 to 15 | |
| | 22-BudAdj | adjustment of the number of buds left after pruning | never or NA$^{a}$ | occasionally or exceptionally | each year | |
| | 23-LfRem | leaf removal | never | occasionally or exceptionally | each year | |
| | 24-LfRTime | leaf removal time | never or NA$^{a}$ | early (flowering) | optimal (bunch closure) | late (veraison) |
| | 25-CluTh | cluster thinning | never | occasionally or exceptionally | each year | |
| | 26-TriMax | maximum frequency of shoot trimming | 0 to 2.1 | 2.1 to 4.1 | 4.1 to 7.1 | |
| | 27-CanoH | maximum canopy height after shoot trimming | 0.8 to 1.2 | 1.2 to 1.5 | 1.5 to 1.9 | |
| *3)* | 31-Lobe | *Lobesia Botrana* control (pest) | none | other strategy (incl. mating disruption) | synthetic pesticide in case of pressure | systematic synthetic pesticide application |
| | 32-Botr | management of *Botrytis Cinerea* (disease) | none | other strategy | synthetic pesticide in case of pressure | systematic synthetic pesticide application |
| | 33-Unci | management of *Uncinula Necator* (powdery mildew ) (disease) | none or other strategy (incl. sulfur) | synthetic pesticide in case of pressure | systematic synthetic pesticide application | |
| | 34-Plas | management of *Plasmopara Viticola* (downy mildew ) (disease) | other strategy (incl. copper) | synthetic pesticide in case of pressure | systematic synthetic pesticide application | |
| | 35-SynMax | maximum$^{b}$ number of synthetic pesticide applications/year | 0 | 0.1 to 7 | 7 to 9 | 9 to 13 |
| | 36-OrgMax | maximum$^{b}$ number of non synthetic$^{c}$ pesticide applications/year | 0 | 0.1 to 6 | 6 to 10 | 10 to 17 |
| | 37-TotMax | maximum$^{b}$ total number of pesticide applications/year | 6 to 8 | 8 to 10 | 10 to 12.5 | 12.5 to 16.1 |
| | 38-ApplR | usual application rate of pesticides in percentage of the MAAR$^{d}$ | less than 50% MAAR$^{d}$ | between - 50% MAAR$^{d}$ and MAAR | MAAR$^{d}$ an NA$^{a}$ | |
| *4)* | 41-Harv | type of grapes harvesting | more than 50% hand harvest | more than 50% machine harvest | | |

$^{a}$ NA = no answer, $^{b}$ in difficult years, i.e.: with humid weather, $^{c}$ allowed in organic agriculture, $^{d}$ maximum allowed application rate

The following annual TMR steps were not included because the variables were not discriminating: “mowing of pruning residues”, “soil management in headlands” and “suckering” (i.e., removal of buds growing on the perennial parts of the vine). Moreover, certain variables, such as the “number of crop protection treatments”, are more informative than others regarding the potential environmental impacts of vineyard management. The “numbers of synthetic” and “organic treatments in the driest years” (minimum) and in the most humid years (maximum) were collected. However, retaining this information for data treatment and clustering both of these variables in addition to those describing the types of treatment per pest or disease would place excessive weight on the crop protection part of the TMR. We chose to keep the “maximum number of treatments” because in difficult years (i.e., the most humid years), the differences in technical choices among the winegrowers are the most obvious, as are the differences in the resilience of the cropping systems with respect to pest and disease risk. The winegrowers were also surveyed about the number of trimmings in dry years (minimum) and humid years (maximum), and, for the same reason, only the humid years were retained for data treatment.

## 3.2 SELECTION OF INDIVIDUALS (= TMR)

The correlation matrix between the 77 surveyed TMRs permitted, after the elimination of redundant TMRs, the retention of a final database of 68 TMRs conducted by 54 different producers.

## 3.3 DATA ANALYSIS RESULTS

### 3.3.1 MCA MAPS AND RESULTS

The TMRs (individuals) are projected on bi-dimensional maps. Each point corresponds to a TMR with its code number. Most of the information is contained in the two maps representing the first 4 dimensions (Figure 7a and b). The projection of the individuals on the first 2 dimensions (Figure 7a) represents 65.3% of the total adjusted inertia. Adding dimensions 3 and 4 (Figure 7b) incorporates 75.1% of the adjusted inertia (Figure 8).

Significance of the first 4 axes of the MCA

The first axis opposes organic and conventional farming systems. It is closely linked on the left-hand side with plant protection and soil management variable modalities that are characteristic of organic viticulture. These variable modalities express the absence of synthetic pesticide use, the maximal use of pesticides allowed in organic agriculture and tillage or grass cover under vines and inter-rows. On the opposite side, the axis is linked to systematic use of synthetic agrochemicals against *Botrytis cinerea*, *Uncinula necator* and *Lobesia botrana* and to mechanical grape harvesting. The upper part of the second axis represents canopy as well as yield management choices with the absence of leaf removal, bud number adjustment and cluster thinning and the lowest canopy height.

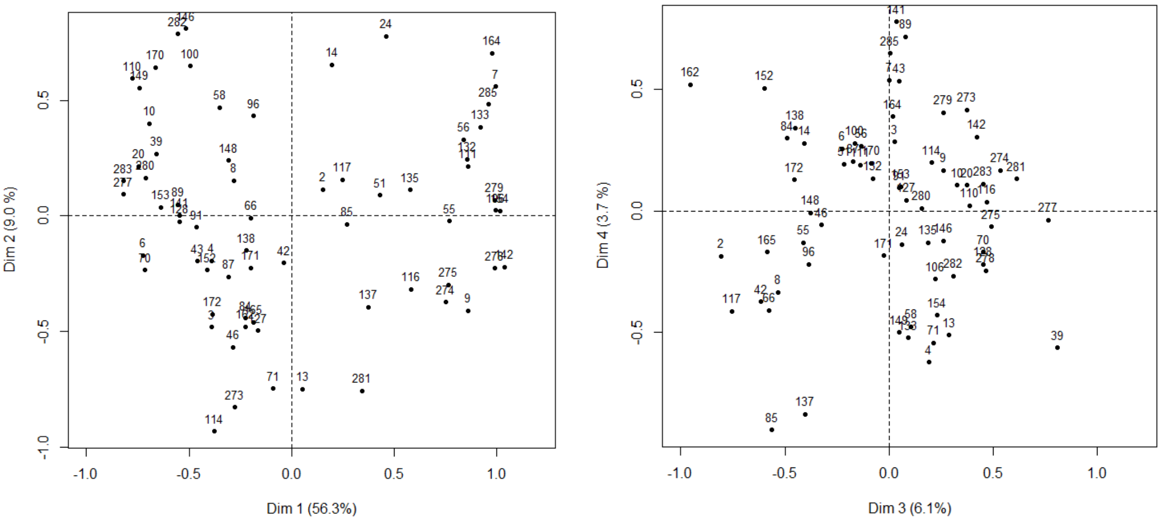


*Figure 7 : a and b MCA maps on the first 4 dimensions*

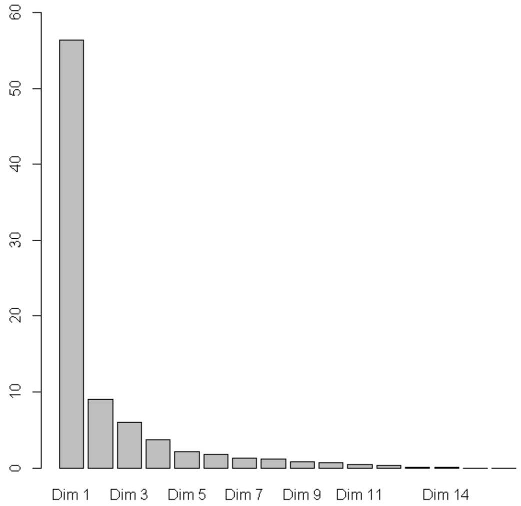


*Figure 8: Adjusted inertia of MCA principal components (in %)*

On the opposite side, the second axis is linked to the maximal yearly number of vineyard treatments in humid years and the use of a moderate number of non-synthetic treatments and grass cover between vine rows.

The third axis is primarily related on the left-hand side to a moderate number of synthetic treatments, reasoned powdery mildew synthetic treatments and occasional bud number adjustments; the right-hand side is related to soil+foliar organic and mineral fertilization. The fourth axis is linked to the lowest annual number of treatments in humid years and late leaf removal at the bottom and to reasoned synthetic treatment against *Lobesia botrana* and soil application of mineral fertilizer at the top.

The individuals are distributed over the entire factor map of the first 2 dimensions, with a higher density on the left-hand side. On the map of dimensions 3 and 4 (Figure 7b), the population is less widely distributed, and the left-hand side of the map is less densely occupied.

### 3.3.2 AHC CLUSTERING AND TREE AND CONSOLIDATION BY K-MEANS PARTITIONING: 5 MAIN TYPES

Five clusters represents the best compromise between a good gain of interclass inertia, a low intra-class inertia and good interpretability of the clusters (Figure 9 and Figure 10).

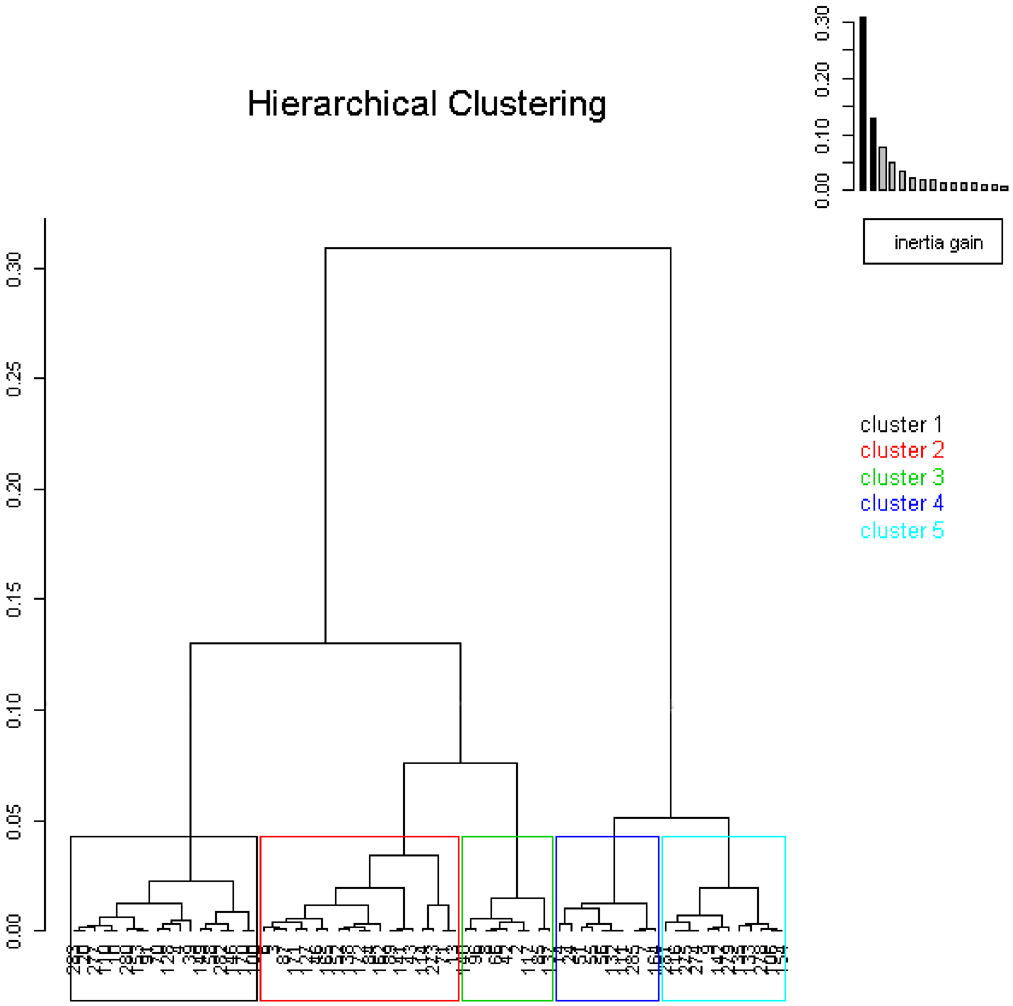


*Figure 9:AHC tree with the 5 clusters before improvement by K-means and inertia gain chart*

After consolidation by K-means, the partition explains 87.3% of the total inertia of the population, which is satisfactory. Thirteen out of 20 variables contribute with very high significance to the partitioning. Plant protection, soil management and harvest variables are the principal contributors, followed by the canopy management variables.

### 3.3.3 TOS LINKED TO EACH CLUSTER: DIVERSITY OF THE POPULATION

The link between clusters and TOs is estimated by a chi² test. A highly significant relationship corresponds to a p value<0.01, a very significant relationship to 0.01>p value>0.001 and a significant relationship 0.05>p value>0.01. A link between a modality and a cluster indicates that this modality is more strongly represented in this cluster than in the other ones. The clusters are represented by different colors in Figure 10.

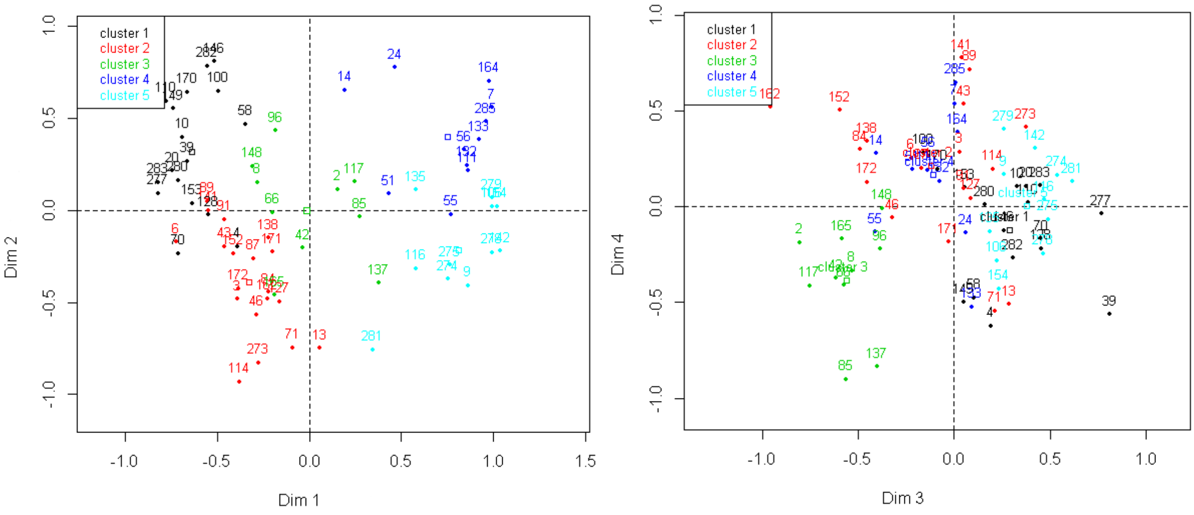


*Figure 10 a and b: MCA maps on the first 4 dimensions with cluster representation; the centroids of the clusters are represented by a square*

Cluster 1 is characterized by “systematic synthetic chemical use and limited handwork”. Cluster 1 is best represented on the 1st dimension, but it is also well represented on the 2nd and 3rd dimensions. It is very significantly linked to 10 variable modalities, the highest number within the 5 clusters. It is primarily characterized by systematic control performed with synthetic products for 3 of the 4 diseases and pests, the absence of non-synthetic product use, the use of herbicides under vines and inter-rows, the absence of soil cultivation, mechanical harvesting, a moderate yearly number of treatments in humid years and an absence of bud number adjustments.

Cluster 2 is characterized by “moderate chemical use”. Cluster 2 is very well represented on the 2nd dimension and well represented on the 1st and 4th dimensions. This cluster corresponds principally to TMRs treated with a moderate yearly number of non-synthetic pesticides and a systematic treatment against downy mildew, a moderate diminution of the pesticide application rate relative to the maximum allowed rate and no pest control without synthetic pesticides.

Cluster 3 is characterized by “minimum synthetic treatments and interventions”. Cluster 3 is very well represented on the 2nd dimension and well represented on the 1st and 4th dimensions. It is characterized with very high significance by only 4 variable modalities: no mineral fertilization, a moderate number of trimming operations, the lowest yearly number of treatments and a moderate yearly number of synthetic pesticide uses. An absence of treatment for *Lobesia botrana* is also a significant characteristic of the cluster.

Clusters 2 and 3 have far fewer significant relationships with variable modalities. These clusters are derived from the same upper branch of the AHC tree, where protection of the vineyard entails a combination of synthetic and non-synthetic pesticides and interventions occur "in cases of heavy pressure" rather than being systematic.

Cluster 4 is characterized as “moderate organic”. This cluster is well represented on the 2nd dimension and specifically characterized by the 3rd level of 4 of the yearly number of non-synthetic treatments. Like cluster 1, it is linked to 10 modalities of TO. Cluster 5 is characterized as “intensive organic”. This cluster is also well represented on the 3rd dimension and characterized by the highest yearly number of non-synthetic treatments.

These 2 last-named clusters (4 and 5) are related to organic TOs. They appear on the same upper branch of the dendrogram with the protection of vineyards by non-synthetic products, grass-covered or tilled soils and manual harvesting. These 2 clusters are both linked with very high significance to 7 and 8 variable modalities, respectively, values that are both much higher than the number of variable modalities linked with clusters 2 and 3. The two clusters are both very well represented on the 1st dimension of the MCA and very highly linked to the absence of synthetic pesticide use, tillage under the vines and fungal control by copper and sulfur.

Generally, canopy and yield management TOs and fertilization do not appear as key descriptors in any of the clusters.

### 3.3.4 REMARKABLE INDIVIDUALS

The 5 paragons and 5 specific TMRs for each cluster identified by K-means partitioning are listed in Table 4 along with their distance to the centroid. In our study, we aimed to identify the vineyard TMRs best representing the main types of management implemented in the region and those that presented the strongest contrasts. Ideally, a parcel that is simultaneously a paragon and specific would be the best parcel (in bold, in Table 4). This occurs for all of the clusters except cluster 2. However, most of the TMRs in this case are not the closest to their cluster centroid except for cluster 5.

*Table 4: Remarkable individuals of each of the 5 clusters identified from the partitioning and their Euclidean distance to the cluster centroid*

| cluster | | paragons | | | | | cluster | | specific | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | parcel n° | 10 | 280 | 20 | **110** | 283 | 1 | parcel n° | 39 | 282 | 146 | **110** | 277 |
| | distance to centroid | 0.250 | 0.250 | 0.284 | 0.356 | 0.374 | | distance to closest cluster's centroid | 1.416 | 1.295 | 1.284 | 1.209 | 1.150 |
| 2 | parcel n° | 87 | 3 | 127 | 172 | 46 | 2 | parcel n° | 114 | 273 | 162 | 71 | 13 |
| | distance to centroid | 0.138 | 0.200 | 0.330 | 0.350 | 0.384 | | distance to closest cluster's centroid | 1.317 | 1.313 | 1.117 | 1.088 | 1.063 |
| 3 | parcel n° | 66 | 42 | **8** | **117** | **2** | 3 | parcel n° | 85 | 137 | **117** | **2** | **8** |
| | distance to centroid | 0.188 | 0.212 | 0.312 | 0.363 | 0.378 | | distance to closest cluster's centroid | 1.331 | 1.240 | 1.033 | 1.027 | 0.874 |
| 4 | parcel n° | 56 | 132 | 111 | **164** | 51 | 4 | parcel n° | 24 | **164** | 285 | 7 | 14 |
| | distance to centroid | 0.152 | 0.194 | 0.219 | 0.454 | 0.460 | | distance to closest cluster's centroid | 1.107 | 1.071 | 1.030 | 1.029 | 0.966 |
| 5 | parcel n° | **275** | **116** | **274** | 9 | **278** | 5 | parcel n° | 281 | **274** | **278** | **275** | **116** |
| | distance to centroid | 0.161 | 0.269 | 0.281 | 0.283 | 0.321 | | distance to closest cluster's centroid | 1.065 | 1.008 | 0.975 | 0.949 | 0.947 |

in bold : TMR that are simultaneously paragons and specific

### 3.3.5 ASSOCIATION OF TOS SPECIFIC TO EACH CLUSTER THROUGH ASSOCIATION RULES

The calculations based on the association rules yielded interesting information about the link between TOs. The association rules concerning 2 items (or modalities) yielded information similar to that represented by a contingency table of 2 variables. For example, the table representing the variable X33.Unci and X34.Plas is shown in Table 5.

*Table 5: Contingency table for the variables management of Uncinula necator (X33.Unci) and Plasmopara viticola (X34.Plas)*

| | X33.Unci=1 | X33.Unci=2 | X33.Unci=3 |
|---|---|---|---|
| X34.Plas=1 | 21 | 0 | 0 |
| X34.Plas=2 | 5 | 2 | 14 |
| X34.Plas=3 | 2 | 12 | 12 |

1 = sulfur, copper or no application, 2 = synthetic treatment in case of pressure 3 = systematic synthetic treatment.

In this table, every parcel treated with copper for *Plasmopara viticola* or not treated at all was not treated or treated with sulfur for *Uncinula necator*. Then, P({X33.Unci=1)} |{ X34.Plas=1}) =1 because the confidence was set to 1. The reciprocal is not true. This assertion could be tested with a chi$^2$ test. For more than 2 variables, the chi$^2$ test would be difficult to perform, in which case the analysis of association rules offers complementary information.

The association rules calculation gave a total of 163,119 rules. Of these rules, 9,109 contained an itemset of length 1 containing a cluster C(1-5) on the right-hand side. The number of rules associated with each cluster and parcel differed strongly between the 5 clusters. Figure 11 shows that the TMRs of clusters 1, 4 and 5 were associated with a significantly higher number of rules. We observe that the higher the number of rules, the higher the homogeneity of the TMRs inside a cluster.

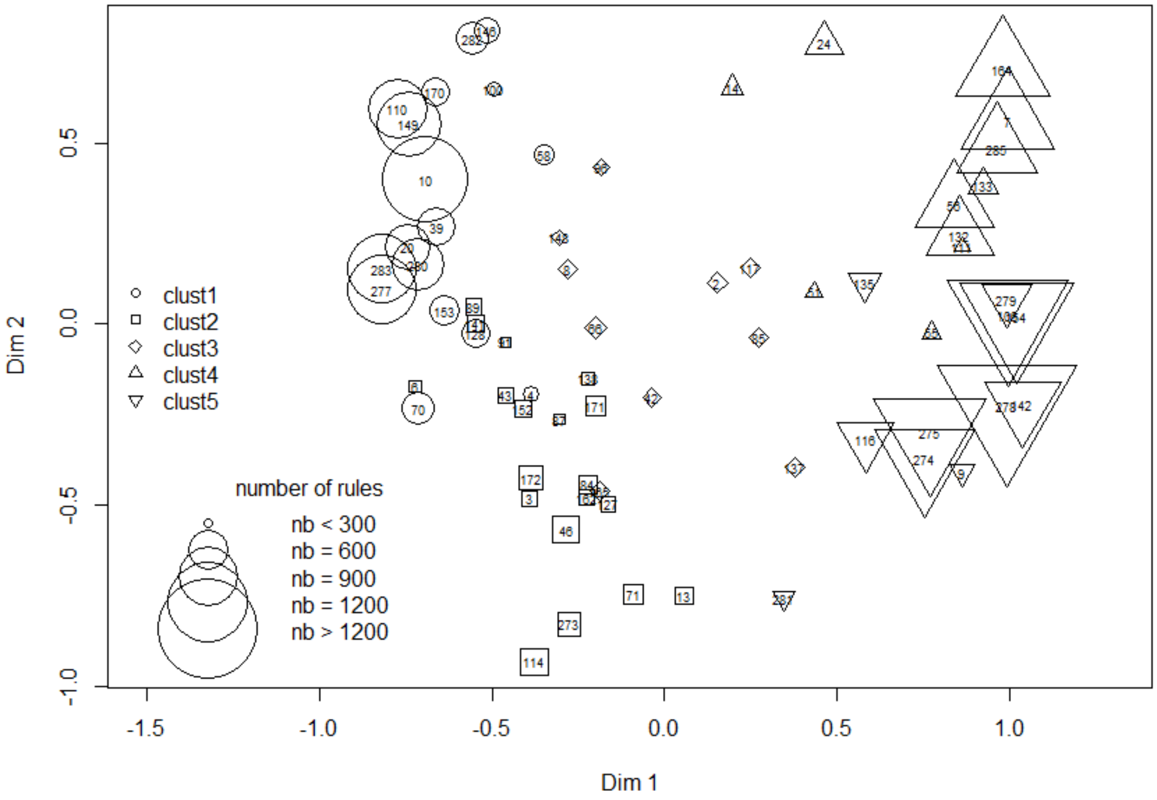


*Figure 11 Number of rules associated with each TMR. The cluster to which the TMR belongs is represented by the form of the symbols on the figure:*

Table 6 shows that the rule with maximal adjusted support is longer for cluster 3 than for cluster 1.

*Table 6:Example of association rules. The rules presented in this table are those with the highest value of adj. support.*

| Rules | v1 | v2 | v3 | v4 | v5 | Cn | sup | conf | lift | adj.supp |
|---|---|---|---|---|---|---|---|---|---|---|
| 8199 | X12.UV.Floor=2 | X32.Botr=4 | X36.OrgMax=1 |  |  | clust=1 | 0.176 | 1 | 4 | 0.70 |
| 38265 | X21.Bud.ha=3 | X36.OrgMax=2 | X38.ApplR=2 | X41.Harv=1 |  | clust=2 | 0.132 | 1 | 3.6 | 0.47 |
| 93179 | X23.LfRem=3 | X26.TriMax=2 | X12.UV.Floor=2 | X01.FertMin=1 | X38.ApplR=3 | clust=3 | 0.102 | 1 | 6.8 | 0.7 |
| 19858 | X27.CanoH=2 | X31.Lobe=1 | X33.Unci=1 | X34.Plas=1 |  | clust=4 | 0.102 | 1 | 6.3 | 0.63 |
| 53271 | X22.BudAdj=3 | X12.UV.Floor=1 | X31.Lobe=2 | X33.Unci=1 |  | clust=5 | 0.147 | 1 | 6.3 | 0.91 |

v= variable, Cn= cluster number, sup= general support, conf=confidence, adj.supp= adjusted support.

In cluster 1, 70% of the parcels are managed in a similar way: tillage under vines (X12.UV.Floor=2), systematic treatment against *Botrytis cinerea* (X33.Botr=4) and no use of organic treatments (X36.OrgMax=1). The choice of a confidence of 1 means that P({clust1)}|{12.UV.Floor=2, X33.Botr=4, X36:OrgMax=1}) =1; thus, if one observes the combination of the 3 modalities, the parcel must belong to cluster 1. The complete analysis of the 9109 rules provides a good characterization of the clusters. The number of rules associated with a cluster, their support and their length demonstrate whether the parcels of one cluster are cultivated in a similar way.

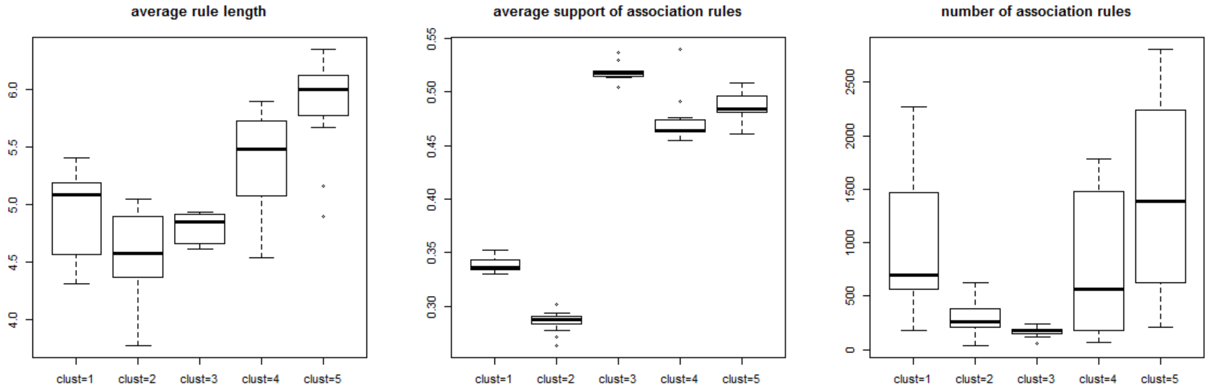


*Figure 12 a to c: Boxplot representations of association rule characteristics according to the cluster*

Figure 12 a-c shows that the average length of the rules is significantly higher for clusters 4 and 5. The average support of association rules is lower for cluster 1 and 2, indicating that these clusters are cultivated in a less homogeneous manner than clusters 3 to 5. Clusters 1 and 5 are significantly more associated with rules. Most likely, this difference is due to standard methods of systematic treatments for cluster 1 and to the constraints given by the organic cultivation techniques for cluster 5. Only a small number of rules are common to the majority of the TMRs of cluster 1. Cluster 2 is more heterogeneous because no association rules concern more than 50% of the TMRs. Cluster 5 exhibits longer rules with a high support. The TMRs of cluster 3 are characterized by a small number of rules that are quite long.

Figure 13 (a and b) shows the maximum length of the rules associated with a cluster with an adjusted support higher than 0.5. The differences are not significant for the support of these rules, in contrast to the length of the rules associated with each cluster. In cluster 5, 54% of the TMRs are associated with a frequent itemset of 10 TOs. Thus, this association rule can be used to characterize the TMRs of this cluster.

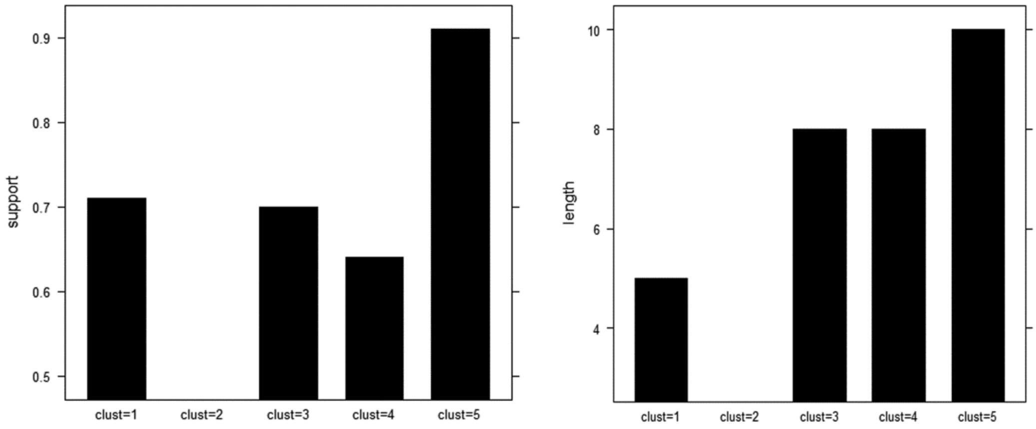


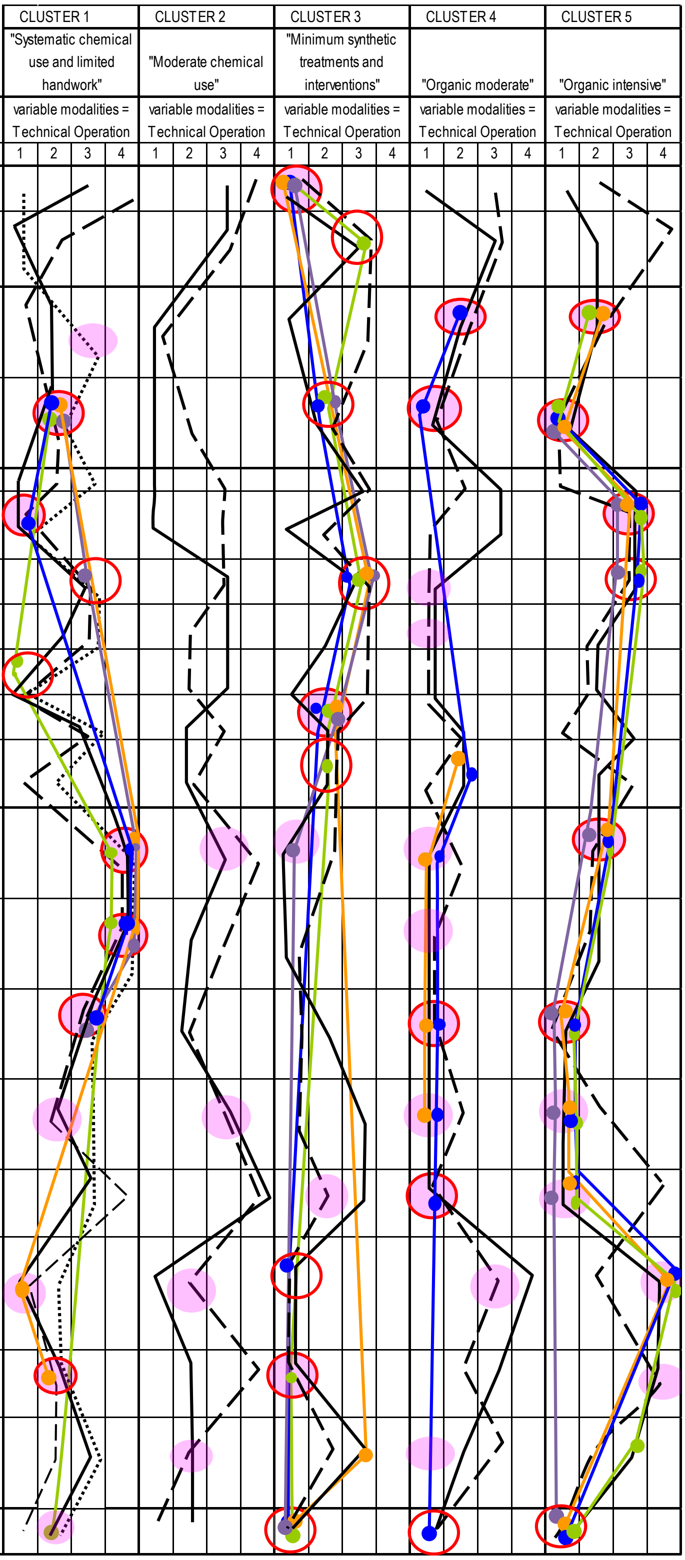
*Figure 13 a and b: Support and maximum length of the rules associated with a cluster with an adj. support higher than 0.5*

## 3.4 SYNTHESIS OF RESULTS FROM THE CLASSICAL AND DATA MINING METHODS

The points of convergence between all methods are represented in Table 7 by red ellipses filled by a pink disc. However, certain TOs do not appear as specific to a given cluster in chi² tests because they are shared with other clusters while they are included in typical association rules (colored lines with dots) and are present in paragon (solid black line) and/or specific (dotted line) TMRs. These TOs are represented on the chart by red ellipses. In contrast, TOs that are highlighted as typical of a cluster by chi² and paragons (pink discs) may not appear in the majority of highly supported association rules.

*Table 7: Synthesis of information on the 5 clusters from classical and data-mining methods*

| variable literal = TMR step | variable modalities = Technical Option 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| mineral fertilisation | none | foliar application | soil application | foliar and soil application |
| organic fertilisation | none | foliar application | soil application | foliar and soil application |
| inter-row floor management | permanent grass cover in all rows | soil tillage in all rows or alternating with grass cover | herbicide use in all rows or alternating with other practice | |
| Under-vine floor management | permanent grass cover or tillage | herbicide use in all rows or alternating with other practice | | |
| number of buds left /m² | 2.4 to 4.3 | 4.3 to 5.4 | 5.4 to 15 | |
| adjustment of the number of buds left at pruning | never or NA* | occasionally or exceptionally | each year | |
| leaf removal | never | occasionally or exceptionally | each year | |
| leaf removal time | never or NA* | early (flowering) | optimal (bunch closure) | late (veraison) |
| cluster thinning | never | occasionally or exceptionally | each year | |
| maximum frequency of shoot trimming | 0 to 2.3 | 2.3 to 4.7 | 4.7 to 7.1 | |
| maximum canopy height after shoot trimming | 0.8 to 1.2 | 1.2 to 1.5 | 1.5 to 1.9 | |
| *Lobesia Botrana* control (pest) | none | other strategy (incl. mating disruption) | synthetic pesticide in case of pressure | systematic synthetic pesticide application |
| management of *Botrytis Cinerea* (disease) | none | other strategy | synhtetic pesticide in case of pressure | systematic synthetic pesticide application |
| management of *Uncinula Necator* (powdery mildew ) (disease) | none or other strategy (incl. sulfur) | synhtetic pesticide in case of pressure | systematic synthetic pesticide application | |
| management of *Plasmopara Viticola* (downy mildew ) (disease) | other strategy (incl. copper) | synhtetic pesticide in case of pressure | systematic synthetic pesticide application | |
| maximum number of synthetic pesticide applications in a year** | 0 | 0.1 to 7 | 7 to 9 | 9 to 13 |
| maximum number of non synthetic pesticide (usable in organic agriculture)applications in a year** | 0 | 0.1 to 6 | 6 to 10 | 10 to 17 |
| maximum total number of pesticide applications in a year** | 6 to 8 | 8 to 10 | 10 to 12.5 | 12.5 to 16.1 |
| usual application rate of pesticides in % age of the maximum allowed application rate (MAAR) | less than 50% MAAR | between - 50% MAAR and MAAR | MAAR an NA* | |
| type of grapes harvesting | more than 50% hand harvest | more than 50% machine harvest | | |



** difficult years * NA = no answer

Key :
Paragons
Specific
The 4 longest associations rules of confidence = 1and adj. support>0.5
Technical options (TO) on which represented rules and remarkable indiviuals converge
TO linked very significantly to the cluster
TO linked very significantly to the cluster and on which represented rules and remarkable indiviuals converge

## 3.5 IDENTIFICATION OF THE BEST CASES FOR FUTURE FIELD RESEARCH

### 3.5.1 IDENTIFICATION OF THE TMR PRESENTING THE SPECIFIC TO ASSOCIATIONS OF EACH CLUSTER

A screening of the TMRs was made in the disjunctive matrix on the basis of the 4 longest association rules of confidence = 1 and adj. support>0.5. The TMRs that have all the most frequent and longest association rules are the most interesting cases. An example is given in Table 8 for cluster 1. Note that in this example, this information completes the information furnished by the remarkable individuals list.

*Table 8: TMR screening on the basis of the 4 longest association rules with confidence = 1 and adj. support>0.5: comparison with remarkable individuals, example of cluster 1. In bold: TMRs having all the association rules.*

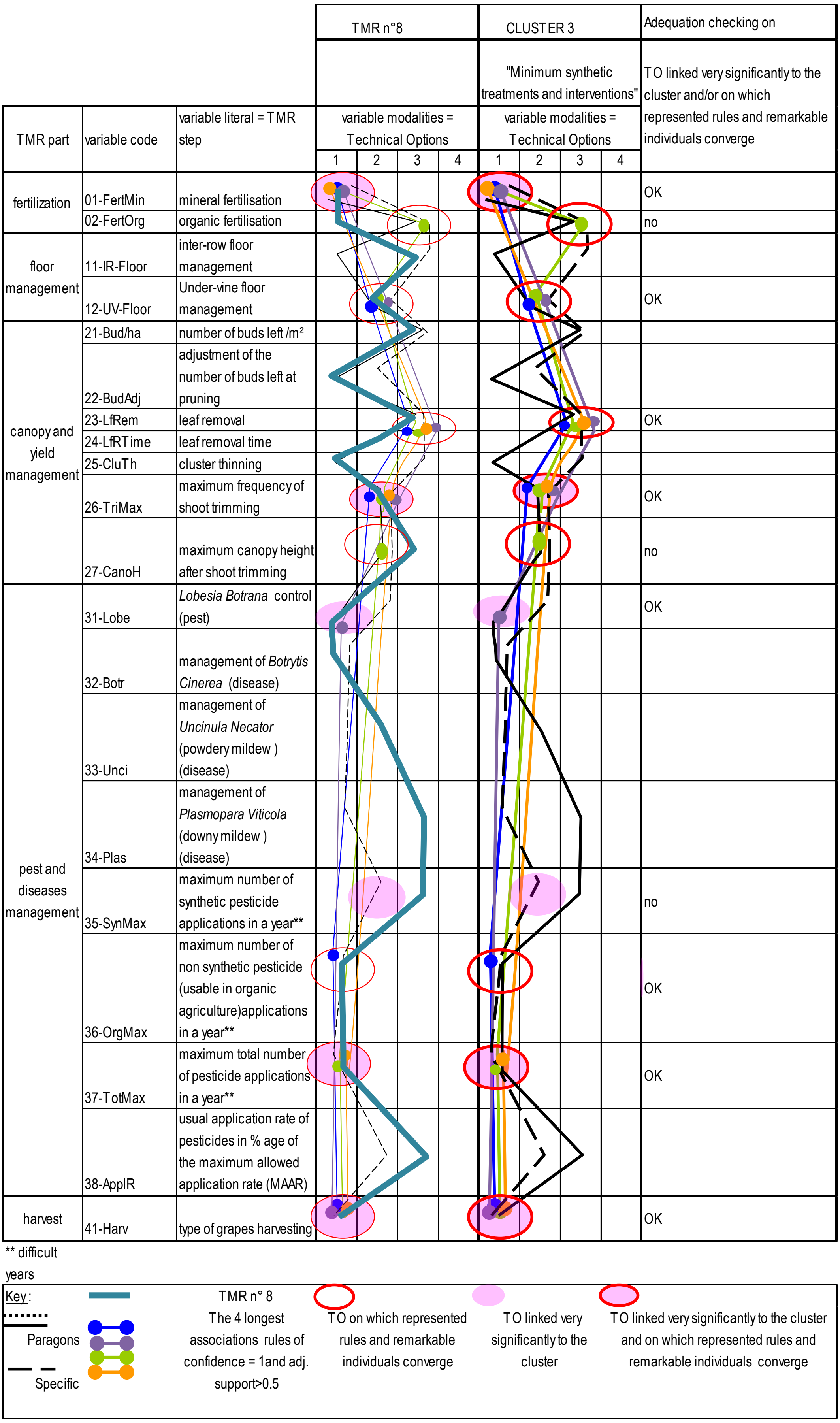
| TMR codes<br>rules number | 4 | 10 | 20 | 39 | 58 | 70 | 100 | 110 | 128 | 146 | 149 | 153 | 170 | 277 | 280 | 282 | 283 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 73884 | | **x** | x | x | | x | | x | | x | | | x | **x** | | x | **x** |
| 73338 | | **x** | x | | | | | x | | x | x | x | | **x** | x | | **x** |
| 74052 | | **x** | | x | | | | x | | | x | x | | **x** | x | x | **x** |
| 74092 | | **x** | x | x | | x | | | | | x | x | | **x** | x | | **x** |
| paragons n° | | 1 | 3 | | | | | 4 | | | | | | | 2 | | 5 |
| distants n° | | | | 1 | | | | 4 | | 3 | | | | 5 | | 2 | |

### 3.5.2 CHOICE OF CASES FROM THE SURVEY SAMPLE

In the present example, all the parcels were chosen from the survey sample. Based on the information provided jointly by the association rules and K-means, a choice of parcels was made in priority within the paragons and the specific TMR pool. It was necessary to incorporate constraints involving distance, motivation/acceptance of the winegrower and availability of useful data for LCA. Accordingly, for one cluster (n°4), a parcel had to be selected from this pool.

For example, TMR n°8 was selected for cluster n°3. This TMR is a paragon and a specific individual. Table 9 shows a comparison of TMR n°8 (in grey blue) with the most typical TOs, the first remarkable TMR and the association rules of its cluster. This TMR contains most of the key TOs and most of the key association rules (except one).

*Table 9: Checking the suitability of a TMR as a study case*



| TMR part | variable code | variable literal = TMR step | TMR n°8<br>variable modalities = Technical Options<br>1 2 3 4 | CLUSTER 3<br>"Minimum synthetic treatments and interventions"<br>variable modalities = Technical Options<br>1 2 3 4 | Adequation checking on<br>TO linked very significantly to the cluster and/or on which represented rules and remarkable individuals converge |
|---|---|---|---|---|---|
| fertilization | 01-FertMin | mineral fertilisation | | | OK |
| | 02-FertOrg | organic fertilisation | | | no |
| floor management | 11-IR-Floor | inter-row floor management | | | |
| | 12-UV-Floor | Under-vine floor management | | | OK |
| canopy and yield management | 21-Bud/ha | number of buds left /m² | | | |
| | 22-BudAdj | adjustment of the number of buds left at pruning | | | |
| | 23-LfRem | leaf removal | | | OK |
| | 24-LfRTime | leaf removal time | | | |
| | 25-CluTh | cluster thinning | | | |
| | 26-TriMax | maximum frequency of shoot trimming | | | OK |
| | 27-CanoH | maximum canopy height after shoot trimming | | | no |
| pest and diseases management | 31-Lobe | *Lobesia Botrana* control (pest) | | | OK |
| | 32-Botr | management of *Botrytis Cinerea* (disease) | | | |
| | 33-Unci | management of *Uncinula Necator* (powdery mildew ) (disease) | | | |
| | 34-Plas | management of *Plasmopara Viticola* (downy mildew ) (disease) | | | |
| | 35-SynMax | maximum number of synthetic pesticide applications in a year** | | | no |
| | 36-OrgMax | maximum number of non synthetic pesticide (usable in organic agriculture)applications in a year** | | | OK |
| | 37-TotMax | maximum total number of pesticide applications in a year** | | | OK |
| | 38-ApplR | usual application rate of pesticides in % age of the maximum allowed application rate (MAAR) | | | |
| harvest | 41-Harv | type of grapes harvesting | | | OK |

** difficult years

# 4 DISCUSSION

We will discuss the 2 dimensions of our proposal: the general model for describing crop management by farmers and the results of the vineyard case study.

## 4.1 FROM DIVERSITY MAPPING TO A CONSOLIDATED TYPOLOGY

Diversity mapping based on MCA allows the identification of the principal drivers of the individual's distribution on the map (Bellon et al. 2001b) and the visualization of the homogeneity of the distribution of the individuals. The Typ-iti generic method allows agronomists to model the diversity of farm management through TMRs at diverse scales from the internal diversity of individual farms to the national level. With a similarity measure given by the distance between groups, we are able to present the successive distances based on diverse hierarchical "cutting procedures". Thus, we aim to use this method on other scales, primarily regional and national.

The Typ-iti method for the TMR completes the methods recently proposed to identify and classify crop successions (Lazrak et al. 2011). Thus, even for annual crops, we now have the opportunity to use statistical and stochastic methods to classify the two main dimensions of cropping systems: the crop succession and the TMR per crop.

In our example, the diversity of the vineyard management of Chenin Blanc for dry wines in the Middle Loire Valley is organized on the first axis of the MCA map (Figure 7a) according to the differences between organic and non-organic management, especially on the basis of the use and non-use of chemically synthesized products. Even if a neat opposition appears between the points at the extreme right and extreme left of the MCA map (Figure 7a), the center of the map is not empty, showing that intermediate management choices between organic and conventional management are found in the sample. This feature of the map is confirmed by the characteristics of the 5 clusters obtained by the typology (§3.3.3): TMR types 1 (systematic chemical use and little handwork) and 5 (organic "intensive") are opposite extremes. Between these extremes, however, there are 3 intermediate types of management (clusters 2, "moderate chemical use"; 3, "minimum synthetic treatments and interventions"; and 4, "organic moderate").

The term "organic" was applied to clusters 4 and 5 in line with the definition of organic agriculture used in the European Council regulation (EC) No 834/2007 (2007), and because, with the exception of one TMR, all members of clusters 4 and 5 were officially certified as "organic farming". The management type adopted by the cluster 3 winegrowers is close to integrated farming as discussed by (Tuomisto et al. 2012) and as precisely defined for viticulture by IOBC (Malavolta and Boller 2009), i.e., interventions with chemicals only if necessary and when neither prophylactic nor natural (i.e., auxiliaries) solutions are possible. The classification combines production philosophy (conventional/reasoned/organic) and intensiveness. Plant protection and soil management strategies dominate the typology. These two TMR parts are, with fertilization, the sites of the major distinctions between organic sets of rules (European-Council 2007) and non-organic vine technical management because they involve the use of external inputs or their alternatives. Note the particular case of downy mildew (*Plasmopara viticola*) disease management: even in cluster 1, "systematic chemical use and limited handwork", the winegrowers apply fungicides against downy mildew only in case of pressure thanks to increasingly advanced risk modeling concerning this fungus (Lafond  et al. 2010). In contrast, powdery mildew (*Uncinula necator*) development is not correctly modeled, and the fungus is very difficult to eradicate once established; this characteristic explains the presence of systematic treatment strategies. Moreover, floor management is affected by the recent evolution of several PDO rules driven by environmental considerations. For example, permanent grass cover of the soil in the headlands recently became compulsory in the PDO considered in the survey (République-Française 2011a, b, c). Furthermore, in the neighborhood, the rules of 2 small PDOs with the highest standards include a ban on herbicide use (République-Française 2011d).

Further treatments of these survey data including other variables should provide greater insight into the links between TMR types and explanatory variables such as PDO; grape or wine trade type; farm size; the winegrower's age, educational level and sensitivity to environmental questions; and the final wine price. These topics will be addressed in a future publication.

## 4.2 CHOOSING THE COMPLEXITY LEVEL TO DESCRIBE THE CROPPING SYSTEMS

The Typ-iti method allows users to choose the number of clusters they want to identify and to characterize the length of the chains of the more strongly linked TOs. Thus the complexity of the TMR in a sample could be managed based on 2 characteristics:

- The number of clusters of similar TMR,
- The number and length of chains of most strongly associated TOs among these TMR clusters (rules).

For the studied vineyards, in a simplified hierarchy, the population can be divided into 3 groups. In this case, we are able to demonstrate a strong similarity between organic vineyard management practices that are strongly associated at the lower level of complexity (see the dendrogram in figure 7); to a lesser extent, a similarity appears between clusters 2 and 3. The strong similarity of the 2 organic clusters is easily explained by a common official set of rules, although the presence of two distinct groups shows that, despite these common rules, significant variability remains in the practices used at the farm level, as noted by (van der Werf et al. 2009; Mouron et al. 2006). However, the Typ-iti method allows the identification of this variability through the use of association rules. The rules show, for example, that choosing a case in cluster 5 will permit a reliable extrapolation of results because long association rules with high support are shared by the majority of TMRs in this cluster. In contrast, extrapolation of the results for cluster 2 will be more uncertain due to the lack of homogeneity of practices indicated by the lack of association rules with high support.

## 4.3 OUTLINING THE MAIN TOS AND THEIR COMBINATIONS TO DESCRIBE THE DIVERSITY OF CROP MANAGEMENT

Our Typ-iti model allows agronomists to describe the diversity of field management and to simplify this diversity by describing the strong combinations of the main TOs. This characterization of diversity is useful for agronomists:

- in their dialogue with farmers and advisers to identify strongly associated techniques, indicating combinations that are therefore difficult to change;
- in their efforts to compare types of farming (Collinson 2000).

For the vineyard example, the most effective discrimination is furnished by the floor, pest and disease management TOs. Grass cover, or cover crop, represents a clearly transitional TO among the clusters. This finding shows that this practice, which characterizes more than 60% of the area of vineyards in the Middle Loire Valley (Agreste-Pays-de-Loire 2013) is not specific to a TMR type. In contrast, herbicide use, combined with synthetic fungicides and insecticides, is typical of group 1, whereas tillage and fungicidal copper and sulfur use are typical of the groups that represent the great majority of organic farming TOs (4 and 5).

## 4.4 IDENTIFICATION OF TOS THAT ARE OFTEN ASSOCIATED: THE HEART OF THE CROPPING SYSTEM CLASSIFICATION

TMR is the management logic used by each farmer in his/her field. As agronomists, we aim to describe farmer TOs through the main dimension of their characteristics, the logical links used by a farmer to associate techniques during a season of production. As a number of agronomic studies have shown, technical operations are linked through a mental logical framework used by each farmer (Debaeke et al. 2009; Le Gal et al. 2011; Papy 2008; Sébillotte 1974; Loyce et al. 2002; Sébillotte 1990).

In viticulture, this logical chain consists primarily of the addition of smaller chains for each part of the TMR as defined in Table 2, Table 3 and Table 7; in theory, these smaller chains are quite independent of each other. Thus, a wide range of possible associations is available to the winegrower. For the same part of a TMR, an example of common association is the link between *Lobesia botrana* and *Botrytis cinerea* control; we observe that the winegrowers usually adopt a similar strategy against both nuisances. The regional statistics mention that 85% of the vineyard surfaces are treated to control *Lobesia botrana*, whereas *Botrytis cinerea* management is not documented (Agreste-Pays-de-Loire 2013). However, the diversity level of logical chains between TMRs changes according to the TMR type. If types (clusters) 4 (organic moderate) and 5 (organic intensive) offer an important case of homogeneity for TMRs, type 2 (moderate chemical use) constitutes a very diverse sample of TO associations. Finally, a strong link appears between the choices all along the TMR (and not only in the individual TMR parts) if these choices are induced by the organic production system, particularly due to the impossibility of synthetic chemical use. Thus, even if floor management does not directly influence the choice of pest management type in theory, these choices appear very closely linked. Therefore, the choice to adopt organic production is very specific in our TMR population, as organic production in viticulture in the Middle Loire Valley represents approximately 7% of the vineyard area (Agreste-Pays-de-Loire 2013) .

The identification of the more closely linked TOs through association rules permits agronomists to identify the principal techniques involved in the TMR built by the farmer. This chain of main techniques, when it can be identified, becomes the major object to address when evaluating the current state of the TMR and changing the TMR. Thus, in a diagnosis or prognosis framework for a cropping system, we must identify these chains of techniques that represent the heart of the TMR.

## 4.5 SELECTING REPRESENTATIVE AND CONTRASTING CASES FOR EXHAUSTIVE EXPERIMENTS OR ASSESSMENTS

The high consistency of the results for partitioning and association rules (Table 7) suggests that the results are quite robust.

Life cycle assessment and agronomic experiments are costly and time-consuming (Coulon-Leroy et al. 2013). If these methods are used, it is essential to select the cases carefully and to ensure their representativeness (Dalgaard et al. 2006). The same crucial question emerges if one seeks to build databases representing the diversity of a given area, e.g., databases of life cycle inventories of agricultural products at the national or continental scale (Eady et al. 2013b; van der Werf et al. 2010). The Typ-iti method allows a reliable choice within a diversity that is characterized by the method and recognizes the links between the TOs selected by the farmers.

In our example, 5 parcels were selected. The selection was made in view of field constraints that sometimes do not permit the choice of the ideal parcel identified by the data analysis.

The joint examination of these parcel TMRs and the synthesis table (Table 7) allows the identification of the points that must be tested in a specific sensitivity analysis and the amplitude of the variations that must be introduced.

## 4.6 SPECIFIC ASPECTS OF VINEYARD MANAGEMENT TYPOLOGY

Certain TMR groups are closely linked with technical guidelines (organic farming/coops). Thus, the adoption of a label at the farming system level influences the choice of TMR at the field level.

The Typ-iti model procedure could be used at a variety of scales, from on-farm surveys to characterization at a regional level. This approach could be very useful for mapping the diversity of the TMR at a regional scale to identify the locations of the diverse cropping systems and the reasons that these locations are structured in this manner. For example, contrasts would most likely appear in the Loire Valley between different PDOs or groups of PDOs, as indicated by the differences in soil management practices between Lower and Middle Loire Valley PDOs (Agreste-Pays-de-Loire 2013).

For agronomists, the knowledge of field management diversity is a first step toward the calibration of their field experiments. The primary advantage of this knowledge-based specification of field management diversity is that the domain of validity of the experiment is known before the experimental results are obtained. In particular, we know the limit of extrapolation of the experimental results based on the knowledge of field management as actually performed by farmers and tested by agronomists.

This diversity of the TMRs could be characteristic of a diversity of PDOs within a region or a country. In vineyard management, TOs are often cited as a characterization of the quality of the final product; they are part of what is termed the “terroir” effect according to the international definition of “terroir” (OIV 2010). Thus, the ability to evaluate the differences among the TMRs gives agronomists a way in which this factor can be objectified for a product as subjective as wine.

## 4.7 LIMITATIONS

The reliability of the results of the Typ-iti method depends on two primary factors:

Data quality and completeness: a complete dataset on technical management is necessary to ensure the quality of the statistical work; data gaps are problematic and can cause the formation of an inaccurate image of the modeled reality. Thus, the method is not suitable for incomplete databases.

The choice of variables is related to the focus of the study. For example, for the purpose of environmental and quality assessment, the variables involved in the analysis were chosen to represent the principal drivers of these 2 topics. This factor means that the use of a pre-existing database might be limited to the use of a database that includes the relevant variables for describing the diversity of TMRs in the frame of a given study. Furthermore, the choice of variables plays a role that must not be neglected in the modeling of diversity. As the results are related, in part, to the choice of variables, this choice must be made rationally as soon as possible in the study (ideally, at the 1st step of the survey: questionnaire design) and refined at the first step of data analysis by eliminating non-discriminating and correlated variables.

The choice of variable modality grouping or variable thresholds is subjective and requires particular care to avoid bias in the results.

Finally, note that the Typ-iti method demands that the user acquire a working knowledge of the data analysis methods, especially association rules, which are seldom used in agricultural data analysis.

## 4.8 GENERICITY

In this study, the Typ-iti method was used to perform diversity characterization and partitioning for a data base on the technical management of vineyards and to select real cases representative of the types of management included in the analysis.

The method is directly applicable to other vineyards by adapting the variables or their modalities to the major local practices and to the study objectives. Similarly, the method can be easily benchmarked to other crops, as any crop management procedure involves chains of practices; for this reason, the database structure will be the same as that presented in this paper. Moreover, even if their combination is new and unique in the Typ-iti method, the statistical tools used here are generic tools that are applicable to any type of object: multidimensional analysis and partitioning have already been applied separately to other agricultural situations, e.g., apple or banana orchards (Bellon et al. 2001b; Blazy et al. 2009); moreover, association rules have been used to identify relationships between land use and quantitative measurements (You et al. 2011; Ekasingh and Ngamsomsuke 2009; Xue et al. 2010).

# 5 CONCLUSIONS

This paper proposes the Typ-iti method, a methodology for constructing a typology and selecting relevant cases for the study of TMRs. This method combines multidimensional analysis, partitioning and association rules. The paper also presents an application of the method to vineyard management. This study represents the first TMR-based typology of a French vineyard using an integrated statistical approach and specific data on farmers' actual practices. The method allows the selection of representative and contrasting TMRs for life cycle assessment and grape quality evaluation and incorporates the links between TOs that are included by winegrowers in their TMRs.

The TMRs are grouped into 5 clusters to define major families according to the most representative TOs. The composition of the clusters is then characterized with a data-mining method to reveal the combination of TOs exclusive to a cluster. The 5 clusters of vineyard TMR are well differentiated, and the similarities vary in intensity within each cluster. Completing the classical typology of TMRs with association rules permits the identification of specific TO associations for each cluster. This procedure identifies the key elements for selecting cases within or outside the surveyed sample of TMRs.

The ability to characterize and differentiate vineyard management is a central topic for many wine regions. Thus, the Typ-iti method could aid all stakeholders involved in the future management of vineyards through a more precise qualification of the diversity of vineyard management.

This first application of the Typ-iti method to a vineyard region allows us to propose it as a basis for future work, primarily the following: i) to aid advisory services and applied researchers in the experimental sampling of TMRs to extend the domain of validity of their future experiments or assessments and ii) to evaluate the regional impact of crop management through an evaluation of the environmental impacts per type and the surface contribution per type.

The Typ-iti method can be benchmarked for other crops, contexts and scales as a protocol for typology and the selection of case studies within a diversity of technical management practices. We hope to initiate a constructive dialogue between agronomists and other stakeholders to strengthen the agronomic contribution to the cropping system diversity chosen by farmers, thereby achieving a shared understanding of the role of this diversity in farming system dynamics.

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## SYNTHESE

L’objectif de ce premier chapitre a consisté à établir une méthode pour choisir des cas réels contrastés et représentant la diversité régionale pour un même objectif de type de vin. Cette étape est essentielle pour mettre en œuvre l’ACV afin d’observer sa pertinence comme aide aux choix techniques à l’échelle parcellaire.

Grâce à la **chaîne de traitement statistique Typ-iti mise au point** ici, nous avons pu partitionner la population enquêtée de 77 itinéraires techniques viticoles (ITKv) de production de raisins de Chenin blanc pour vins blancs secs AOC en Moyenne Vallée de la Loire. Cette partition aboutit à **5 groupes d’ITKv** : 1-«traitement systématique de synthèse et travail manuel limité », 2 « usage modéré de traitements », 3 « traitements de synthèse et interventions minimaux », 4 « biologique modéré » et 5 « biologique intensif ». Ces groupes ont été caractérisés par trois éléments : les choix techniques qui leur étaient spécifiques, les associations de choix techniques les plus fréquentes qui leur étaient propres et leurs individus remarquables, à savoir les ITKv les plus représentatifs : les parangons et les spécifiques. La synthèse de ces éléments dans une représentation graphique originale a permis de disposer des critères à privilégier pour rechercher dans le vignoble, parmi les parcelles sur lesquelles nous disposions d’informations sur leurs conduites, des parcelles dont les ITKv représentaient chaque groupe le plus fidèlement possible.

## TRANSITION

Le chapitre suivant s’attache à résoudre un verrou méthodologique préalablement à la mise en œuvre de l’ACV. Il s’agit de pouvoir estimer les émissions de pesticides suite à leur application au vignoble. Le manque de modèle d’émission adapté aux conditions spécifiques de la viticulture nous a amenée à travailler avec les concepteurs du modèle PestLCI2.0, outil le plus avancé pour le calcul des émissions potentielles de pesticides au champ en agriculture, afin de l’adapter à la viticulture. Un schéma du principe du modèle a été ajouté dans la thèse pour faciliter la compréhension.

# CHAPITRE 3

# PESTICIDES EMISSIONS MODELING AND FRESHWATER ECOTOXICITY ASSESSMENT FOR GRAPEVINE LCA: ADAPTATION OF PESTLCI 2.0 TO VITICULTURE

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# KEYWORDS

Life cycle assessment, vineyard, emissions, fate, plant protection product, agriculture, USETox$^{TM}$

# ABSTRACT

## Purpose

Consumption of high quantities of pesticides in relation to viticulture farming emphasizes the importance of including pesticide emissions and impacts hereof in viticulture LCAs. This paper addresses the lack of inventory models and characterization factors suited for the quantification of emissions and eco-toxicological impacts of pesticides applied to viticulture. The paper presents i) a tailored version of PestLCI 2.0, ii) corresponding characterization factors for freshwater ecotoxicity characterization and iii) result comparison with other inventory approaches.

## Methods

The customization of the PestLCI 2.0 model for viticulture includes: i) addition of 29 pesticide active ingredients commonly used in vineyards; ii) addition of 9 viticulture type specific spraying equipment and accounting the number of rows treated in one pass; iii) accounting for mixed canopy (vine/cover crop) pesticide interception.

Applying USEtox™, the PestLCI 2.0 customization is further supported by the calculation of freshwater ecotoxicity characterization factors for active ingredients relevant for viticulture. Case studies on three different vineyard technical management routes illustrate the application of the inventory model. The inventory and freshwater ecotoxicity results are compared to two existing substance generic emission quantification approaches.

## Results and discussion

The assessment results show considerably different emission fractions, quantities emitted, and freshwater ecotoxicity impacts between the different active ingredient applications, and that 3 out of 21 active ingredients dominate the overall freshwater ecotoxicity: Aclonifen, Fluopicolide and Cymoxanil.

The comparison with two substance generic approaches, which consider field soil and air as part of the ecosphere, shows that PestLCI 2.0 yields considerable lower emissions and, consequently, lower freshwater ecotoxicity.

The sensitivity analyses reveal the importance of soil and climate characteristics, canopies (vine and cover crop) development and sprayer type on the emission results. These parameters should therefore ideally be obtained with site specific data, while literature or generic data are acceptable inputs for parameters whose uncertainties have less influence on the result.

## Conclusions and recommendations

Important specificities of viticulture have been added to the state of the art inventory model PestLCI 2.0. The customization covers vertically trained vineyards, which is the most common vineyard training form; the model can also be used for other perennial or bush crops provided equipment, shape of the canopy and pesticide active ingredients stay in the range of available options. A similar and compatible model is needed for inorganic pesticide active ingredients emission quantification, especially to account for organic viticulture impacts.

# 1 INTRODUCTION

Wine production benefits from a "green industry" image (Berghoef and Dodds 2013; Christ and Burritt 2013; Brugière 2009). Due to the high pest sensitivity of vine, wine industry however applies 13% in mass of all synthetic pesticides used in Europe, while it occupies only approximately 3 % of the European cropland (Muthmann and Nadin 2007), which is in accordance with observations made in California (Christ and Burritt 2013), where the share of viticulture in terms of pesticide consumption also is larger than its share in agricultural land use. Numerous environmental concerns are related to pesticide use, like surface and groundwater contamination, contaminated runoffs from the fields, bee poisoning (Christ and Burritt 2013) and/or emission of toxic active substances to the air compartment (ATMO Drôme-Ardèche et al. 2010; Ducroz 2006). For these reasons, and due to the considerable contribution from pesticide active ingredients (PAIs) to impacts in agricultural products LCAs (Bessou et al. 2012; Godard et al. 2012; Vázquez-Rowe et al. 2012b), emissions of PAIs are a key topic to be addressed when performing wine and/or grape production LCAs.

Due to the lack of viticulture-specific inventory models capable of quantifying pesticide emissions and limited availability of characterization factors (CFs) for relevant PAIs, most of the published wine LCA studies neglect toxicological impacts from PAI emissions (Ardente et al. 2006; Benedetto 2013; Bosco et al. 2011; Gazulla et al. 2010; Pattara et al. 2012; Point et al. 2012). Other authors considered substance generic pesticide emission fractions as Neto et al.(2012) such as 25% to the air and 75% to the soil or as Petti et al.(2006b) who in an LCA of organic viticulture assumes that 50% of a copper pesticide is absorbed by the plant and 50% reaches the soil before continuing on to the groundwater compartment (i.e. hence disregarding issues such as drainage system interception of percolate etc.). Regarding other crops, Nemecek and Schnetzer (2011) assume for all agricultural crop pesticide inventories that 100% of the applied pesticides are emitted to the soil.

Vázquez-Rowe et al. (2012b) and Villanueva-Rey et al.(2014a) were the only authors using a substance specific model to estimate pesticide emissions in wine or wine grape LCAs. Both assessments applied PestLCI 1.0 (Birkved and Hauschild 2006). PestLCI is a dedicated inventory model intended to calculate organic pesticide emissions from arable land (technosphere) to the environment (ecosphere) to be used in (life cycle) impact assessment modelling.

PAI emissions vary and are results of interactions between the properties of the PAIs, the local environment (including meteorology) and agricultural practices (Aubertot et al. 2005a). This substance- and context dependency is taken into account by PestLCI, which is currently the most advanced LCI model for PAI emissions from agricultural fields (van Zelm et al. 2014). The most recent version of the model, PestLCI 2.0, described in Dijkman et al. (2012) and further modified as described in Dijkman (2014), covers app. 90 active ingredients of various types of pesticides, 25 European climate profiles and 7 European soil profiles. Two steps of emission are modelled in PestLCI, primary (distribution between air, soil, and plants at spraying time) and secondary distribution (fate of the substances until they cross the field borders) (see figure 13 bis).

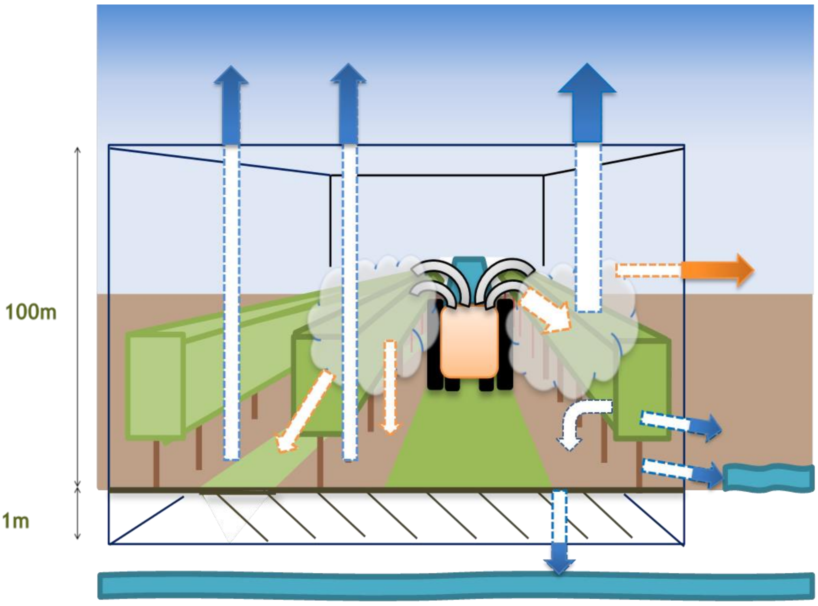

Figure 13-bis: *principle of PestLCI model pesticide emission calculation illustrated for vineyards. Primary distribution is represented by orange dotted arrows and secondary distribution is represented by blue dotted arrows. The quantities emitted out of field boundaries are represented by solid parts of the arrows.*

Despite the rather extensive coverage in terms of pesticides, climates and soils, PestLCI 2.0 does not take into account certain specificities of viticulture like double cropping system, vertical spraying, specific PAIs etc., which differentiate viticulture from other crops and influence the pesticide emission patterns from viticulture compared to other crops. The aim of this paper is to present a tailored version of PestLCI 2.0 customized to appropriately account for the viticulture specificities influencing pesticide emission, and to compare the results of this approach to that of other substance generic LCI approaches.

This paper addresses successively: i) the inclusion of specificities of viticulture in the customized PestLCI 2.0 version ii) the development of CFs for freshwater ecotoxicity (FwEtox) using the USEtox™ characterization model for viticulture specific PAIs not covered by the current USEtox CF database , iii) the application of the customized inventory model, on a case study of three different conventional2 vineyard Technical Management Routes (TMRs3). The application is further supported illustrated by characterization of the freshwater ecotoxicological impact potentials through combination of emission quantities and FwEtox characterization., iv) a sensitivity analysis of PestLCI 2.0 for the identification of the most influential inputs of the model.

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[2] « Conventional » will be used in this paper to designate non-organic plant protection practices

[3] technical management routes (TMRs): logical successions of technical options designed by the farmers (Renaud-Gentié et al. 2014))

# 2 METHODS

## 2.1 CUSTOMIZATION OF PESTLCI 2.0

In order to improve the viticulture specificity of PestLCI 2.0, the model was updated with 29 pesticides frequently used in European viticulture, 34 vine and cover crop development stage combinations as well as 9 viticulture specific pesticide application techniques typically employed in French viticulture. Moreover, 5 Loire Valley soil profiles, 22 French temperate maritime climate profiles were added to the data foundation. A summary of all updates is presented in table S1 in the Supplementary material. The customization undertaken is designed for modelling of vertical shoot positioning trained vineyards, which by far is the most frequent training system[4] for vineyards in France and other wine producing countries. In the remainder of this section, the aforementioned updates are described in more detail. Most of the updates include an expansion of the PestLCI 2.0 databases. The new data included in the model can be found in the Online Resource.

The modelling of buffer zones around the field was altered, so that the model user can indicate whether a freshwater body is located near the field. If this is the case, the user has to specify the distance to the water body. In case this distance is less than the required buffer zone around the field, a part of the field will be considered a part of the buffer zone between the area undergoing pesticide application and the freshwater body. If there is no water body nearby, any surface runoff from the field will be considered as an emission to the soil outside the field, therefore a compartment was added: nearby agricultural soil.

### 2.1.1 ACTIVE SUBSTANCES FOR PEST, DISEASES AND WEED MANAGEMENT IN VITICULTURE

An average number of 16 pesticide active ingredients (PAIs) was applied to French vineyards in 2010 (with high interregional variability). Downy and powdery mildew fungi were the target pests in 95% of the 12 applications (Ambiaud 2012b).

A variety of PAIs are registered for viticulture farming in Europe, from generic farming PAIs to more crop specific PAIs shared with pest management in vegetables or in orchards. The latter pesticide types were not available in the original PestLCI 2.0 version. Hence, on the basis of the list of the viticulture specific PAIs applied over 4 vintages (2010 to 2013) on 3 application cases (see Supplementary material, table S2), compilation of data on the properties of the relevant organic PAIs used in viticulture was conducted applying dedicated chemical/fate property databases (refer to Supplementary material section S-C and table S3 for a more thorough introduction to the missing viticulture relevant PAIs in PestLCI 2.0).

Inorganic fungicides based on copper and sulfur are widely used in viticulture, especially organic viticulture (see more details on vine pests and diseases management, copper and

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[4] Training system: type of trellis and shoot positioning resulting to a given shape of the vine canopy and position of grapes.

sulfur in the Online Resource, sections S-A and S-B). Sulfur represented, in 2003, 69% in mass of the PAI applied in the European Union on vineyards, and cupric compounds, 2.7% (Muthmann and Nadin 2007). Conventional viticulture also uses other inorganic PAIs such as ammonium thiocyanate (herbicide) or partially inorganic PAIs like fosetyl-Al (fungicide). However, inorganic or partially inorganic substances behave and react differently compared to entirely organic5 pesticide due to speciation. Their emissions loads can't hence be modelled, as organic pesticides, applying PestLCI 2.0. For this reason, these types of PAIs were not included in this study.

In addition, more "exotic" PAIs were likewise not considered in the present study. This third PAI group includes:

- PAIs not officially approved/registered as pesticides such as algae extracts (only registered as fertilizers)
- pesticide formulation additives (e.g. light paraffinic oil, canola oil, glycerol and lignite), due to lack of information about their properties and occurrences in the assessed pesticides, despite the fact that these substances can contribute considerably to toxicity of the pesticide formulation (Brausch and Smith 2007) and modify PAIs drift potential (Celen 2010).

### 2.1.2 SPRAYING EQUIPMENT FOR APPLICATION OF PESTICIDES

PestLCI 2.0 takes into account the type of sprayer used for the application of the pesticide in order to quantify the drift through drift curves. The types of spraying equipment applied in viticulture are numerous, which makes the task of modeling the individual equipment characteristics a challenge. The sprayers designed for canopy and grapes spraying may use different modes of droplets production and conveying: non air-assisted spray, airblast and pneumatic. Different shapes of the ventilators and of the sprayers themselves lead to different patterns in terms of spraying quality and drift generation.

None of the above presented culture specific application techniques were available in PestLCI 2.0. In the present customization of PestLCI 2.0, 9 new viticulture specific sprayers were included. The 9 sprayer types are described in table S7 in the supplementary material. Of these, a tunnel sprayer based on data by Ganzelmeier (2000) and 8 item from (Codis et al. 2011), who published the only drift curves obtained in France for vineyards according to the ISO protocol (ISO 2005b), for 8 different vineyard spraying equipment. We assumed that the bias caused by the vine rows width difference between Codis et al. (2011)'s test setup and our modelling approach (1.40m compared to ours are 1.90 to 2.50m) would lead to smaller uncertainties than relying on data for non-viticulture specific spraying equipment. From the results of these 9 drift measurements, drift curves were derived. These are given in table S87 in the Online Resource.

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[5] « Organic » is alternately used in the paper to qualify a type of crop management which uses no synthetic pesticides, and a chemical type of PAIs: organic chemical compounds containing covalent bound carbon, oppositely to inorganic chemical compounds (inorganics) which do not contain carbon bound this way. Here "organic" relates to the chemical compound nature.

According to the design of the sprayer, winegrowers can choose to spray one to four rows of vines simultaneously. The number of rows treated plays a significant role in wind drift calculation in PestLCI 2.0. This issues has been taken into account by entering the actual width treated at the same time along with the parameter ”nozzle distance” in the model.

Herbicides are most often applied very close to the soil with specific sheltered booms to avoid herbicide drift and hence deposition on vine leaves. We chose to model this application technique as the existing “soil incorporation” in PestLCI 2.0 since sheltered boom sprayers induce very low drift.

Finally, modelling of custom spray techniques covering various adaptations of existing spraying equipment is considered beyond the scope of this paper.

### 2.1.3 ACCOUNTING FOR PRIMARY DISTRIBUTION IN DOUBLE CROPPING SYSTEMS

Cover cropping on vineyard soil is a developing management scheme with nearly half of the French vineyards temporarily or permanently applying double cropping (Ambiaud 2012a). A second canopy under the vineyard (e.g. spontaneous species, oats, clover or fescue) can cover various proportions of the row width and present various densities. The secondary crop contributes to pesticide interception (primary distribution) and fate (secondary distribution), which increases the pesticide’s potential for volatilization while limiting runoff from topsoil.

The primary distribution process is defined in PestLCI by 3 factors: wind drift ($f_d$), pesticide deposition on soil ($f_s$) and pesticide deposition on leaves ($f_l$) (Birkved and Hauschild 2006). The two latter are based on (Linders et al. 2000) interception factors for single crops at different development stages. In terms of interception by the vine canopy, PestLCI 2.0 includes interception values for vine at four different development stages I, II, III, and IV based on (Linders et al. 2000). We added an additional stage 0 to the model in order to take into account situations of leafless vines (see supplementary material S-D for details). We further adjusted vine interception fractions by considering results of on-field measurements of spraying mixture deposition and losses on vineyards by Sinfort (pers comm 2014 and Sinfort et al. 2009) and on artificial vineyard by (Codis et al. 2014)). Distribution ratios of spray mixtures between vine canopy, soil and air at 2.5 m above the soil were obtained by these authors in vineyard conditions similar to the ones we study (rows width, types of sprayers). The fraction sent to air during an application measured by these authors was introduced in PestLCI 2.0 as being i) partly conveyed by wind drift out of the parcel (i.e. advective transport), and ii) partly falling back on vegetation and bare soil of the parcel (i.e. sedimentation). This choice was made because no quantification of direct volatilization during spraying is possible (Jensen and Olesen 2014) due to the complexity of volatilization driver combinations (properties of the spray liquid, drops size and drops surrounding conditions)(Gil et al. 2008) and the lack of available data for some of the equipment specific parameters. The details of these drift calculation including equations are available in the Supplementary material section S-D.

The interception by the cover crop, as modelled in the version of PestLCI 2.0 presented in this work, varies according to the width of the cover crop strips estimated as a percentage of the width of the vine inter-row, and according to cover crop canopy density (see Figure 14-pictures 1 to 3).

*Figure 14: pictures 1-3 vine I grass 0%; vine I, grass 100% average density; vine IV grass 50% high density (pict. 1 and 2, E Bezuidenhoud, pict.3 : P. Rodriguez-Cruzado)*

A consequence of this change in emission modelling compared to a situation in which cover crop is not present, is that, in the initial distribution, less pesticide will reach the soil, and more will be present on vine and grass leaves, meaning the fraction intercepted by the crop canopies increases compared to monocultures. As a consequence, less runoff of dissolved pesticide and volatilization from top soil should be expected. On the other hand, more pesticide can be expected to volatilize from the leaves of the cover crops. In general, volatilization rates are higher from leaves than soil, so for most pesticides an increase in emissions to air can be expected.

Combined interception factors for mixed canopies (vine+cover crop) were included in the model for the most typical situations as the following product: [vine development stages x cover-crop strip width x grass canopy density] (see Table 10).

*Table 10: Examples of combined interception factors for vine/cover crop mixed canopies (complete table available in the Supplementary material table S4)*

| **Stage** | **density of cover crop canopy** | **% of soil surface covered by cover crop** | $f_{\text{vine}}$ | $f_{\text{covercrop}}$ | **% spray intercepted by vegetal soil cover *(calculation)*** | $f_{\text{global}}$ |
|---|---|---|---|---|---|---|
| 0 | none | 0 | *0.1* | 0.3 | 0% | 0.10 |
| II | weak (30%) | 100% | 0.5 | 0.3 | 6% | 0.56 |
| II | high (70%) | 80% | 0.5 | 0.7 | 11% | 0.61 |
| III | average (50%) | 100% | 0.65 | 0.5 | 5% | 0.70 |

### 2.1.4 CLIMATE AND SOILS DATASETS

Site specific climatic profiles appropriately representative for the case study areas were included in PestLCI 2.0. To permit sensitivity tests on climate data, two sets of 30 years average 1971-2000 and 1981-2010 for the Beaucouzé Station were added to PestLCI, as well as data from five stations of the Middle Loire Valley, located close to the studied vineyards. For these five stations data for 3 years of production, i.e. October year n to September year n+1, for 2009-2010 to 2011-2012, as well as sets of average months for the 3 years are available see table S5 in the Supplementary material. Climatic data were provided by Météo France. Five soils corresponding to the modelled parcels were characterized through measured data and observations, in accordance with the PestLCI 2.0 data requirements, and entered in PestLCI 2.0., see table S6 in the supplementary material.

### 2.1.5 MODELLING OF PESTICIDE RUNOFF FROM THE FIELD SURFACE

The modelling of buffer zones around the field was altered. In previous versions of PestLCI, the width of the buffer zone was fixed, independent of both the presence of surface water, which these zones are intended to protect, and the distance to this surface water. In the updated model, the user can indicate whether a freshwater body is located near the field. If this is the case, the user has to specify the distance to the water body. In case this distance is less than the required buffer zone around the field, a part of the field will be considered a part of the buffer zone between the area undergoing pesticide application and the freshwater body. If there is no water body nearby, any surface runoff from the field will be considered as an emission to the soil outside the field, therefore a compartment was added: nearby agricultural soil. Soil was chosen as an emission compartment, because this compartment better represents the fate of the pesticide than other environmental compartments. When surface water is not nearby, the runoff water will end up on or in the soil, and the pesticide will partition between the soil solid matter and the air and water in the soil pores. Emissions to this compartment were characterized as emissions to continental agricultural soil in USEtoxTM.

### 2.1.6 CALCULATION OF USETOX™ CFS

CFs are needed in LCA to quantify the potential environmental impacts resulting from emissions occurring over the life cycles of products and systems. CFs are generally substance and compartment specific and sometimes spatially explicit since the impact pathways of an emission depends on the substance, the emission compartment and to some extent the geographic location of the emission. In this study, we used CFs obtained from the USEtox™ characterization model since the model was developed as a scientific consensus model, supposedly representing the best application practice for characterization of toxic impacts of chemicals in LCA (Hauschild et al. 2008) and since its database (v. 1.01) covers ~2500 chemicals with calculated CFs for FwEtox (Rosenbaum et al. 2008). USEtox™ is not spatially resolved, but operates with a nested structure that distinguishes between an urban (air compartment only), continental and global scale.[6] Following common practice we applied CFs from the USEtox™ database (v. 1.01) for emissions to the continental air, agricultural soil and freshwater compartments. Of the 48 PAIs covered by this study, the default USEtox™ database currently does not cover 21 (see table S2 in the Online Resource). To fill these gaps we applied the USEtox™ model to calculate CFs for emissions to the continental air and freshwater compartments for the 18 organic PAIs of the 21 PAIs missing in the default database (the USEtox™ model is not designed to characterize inorganic emissions, hence 3 inorganic PAIs were left out). Leaving out these 3 pesticides will have some effect on the results, however lacking emission and characterization data on the 3 substances left out obstruct assessment of the errors introduced hereby.

Due to the considerable contribution to the total impact score from Folpet and the calculation of a much lower CF by AiiDA (Hugonnot et al. 2013), we recalculated the CF for Folpet based on best available data. We found that input parameters related to physical-chemical properties of the PPDB (University-of-Hertfordshire 2013) database were generally of a higher quality (more experimental values) than the data from the EPISuite (US-Environmental-protection-Agency 2012) used in the calculation of the Folpet CF from the default USEtox™ database. We therefore recalculated CFs based on PPDB input data (where these were available) for physical-chemical properties, but did not change “avlogEC50” (the input parameter for ecotoxicity), since this parameter was based on test data from 26 species, representing 4 trophic levels and therefore deemed to be of a high quality. The input data used for recalculating the CFs of Folpet and the resulting set of CFs are presented in Table S9 and Table S10 (supplementary material).

Since USEtox™ is spatially generic these new CFs may be applied to case studies anywhere in the world. The calculations followed the procedure of the USEtox™ manual. Experimental data inputs were prioritized over modelled data inputs (see Table S9 and S10 for data sources and data used). Regarding uncertainties of the calculated CFs, we followed the classification of the USEtox™, which flags CFs as “interim” if a number of criteria for (relatively) low uncertainty are not fulfilled.

### 2.1.7 CASE STUDY

Three contrasted conventional TMRs of *Chenin Blanc* cultivar in the Middle Loire Valley (France), studied during 2010-2011 production year were chosen to illustrate the applicability of the PestLCI 2.0 customization for viticulture and new USETox$^{TM}$ CFs. The cases presented here are part of a project aiming to establish a method for joint evaluation of environmental (through LCA) and qualitative performances of viticultural TMR (Renaud et al. 2012).

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[6] USEtox$^{TM}$ contains no ground water compartment. Ecotoxicological impacts in freshwater from chemical emissions to groundwater are considered negligible and thus not further considered in this study.

### 2.1.8 FUNCTIONAL UNIT

The emissions and impacts calculated in our paper are presented per ha because vine, as a perennial crop, occupies land for several decades (sometimes centuries) and vineyards in addition have an important function of maintaining space and landscape values (Joliet 2003; Renaud et al. 2012). Moreover, this functional unit accounts for the goal of minimizing the impacts while cultivating a given area (Mouron et al., 2006), and it is hence considered more adequate for communication towards winegrowers who typically reason in terms of farming management practice per ha. The emissions and impacts can, if needed, be calculated per kg of grape, by dividing the results by the yield of each parcel.

### 2.1.9 GEOGRAPHICAL SITUATION, CULTIVAR AND PRACTICES

The Middle Loire Valley's cool and sub-humid climate (Tonietto and Carbonneau 2004) offers favorable conditions for growing different sorts of vine (*Vitis Vinifera*) cultivars and producing a wide range of wine types in more than 50 different wine production areas labelled "Protected Denominations of Origin" (PDO[7]). Chenin Blanc is the typical and the main white cultivar of this area, used to produce dessert-style sweet, dry and sparkling white wines. The three vineyard TMRs chosen for the present study are designed for PDO Chenin Blanc dry wine production in the PDO zones Anjou Blanc and Saumur Blanc. The soils and subsoils of the Anjou PDO zone are mainly schist and metamorphic sandstone of the Armorican Massif, while the Saumur PDO zone is located on the sedimentary marl, chalk and calcareous sands of the Parisian Basin (Goulet and Morlat 2011). Despite the PDO set of rules fixing some practices, like training system or rows width (similar for the PDOs represented in the present survey) an important diversity remains for the other practices. The three TMRs studied are all represented by real vineyard situations. The choice of these three real situations was based on the results of a regional survey analyzed according to Typ-iti method (Renaud-Gentié et al. to 2014), in order to represent the diversity of vineyard management of Chenin Blanc grown for PDO dry white wines production in Middle Loire Valley. Five types of vineyard TMRs emerged from this survey analysis: (1) "systematic synthetic chemical use and limited handwork", (2) "moderate chemical use", (3) "minimum synthetic treatments and interventions (i.e. mechanical or manual operations)", (4) "moderate organic" (i.e. with limited interventions and treatments), (5) "intensive organic" (i.e. with many interventions and treatments). All 5 TMRs are further described in (Renaud-Gentié et al. 2014). The cases studied in the paper at hand concern practices of the winegrowers observed on 3 plots representative of the three first TMR type, the two last TMR types are organically managed and thus involve nearly exclusively inorganic PAIs which are not modelled in PestLCI 2.0.

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[7] PDOs promote and protect names of quality agricultural products and foodstuffs which are produced, processed and prepared in a given geographical area using recognized know-how (European-Commission 2014).

### 2.1.10 CLIMATE OF THE STUDIED YEAR

The results presented here relate to production year 2010-2011(Oct1st 2010-Sept 30th 2011). Based on the Angers-Beaucouzé weather station (main station of the area) data, the production year 2010-2011, in comparison to the average of 30 years 1981-2010 (Figure 15), 2011 can be described as: i) a little warmer (+0.2° on the annual average) with a warmer spring but a cooler July, ii) much drier especially during the vine growing season (-60 mm rain and + 40 mm potential evapotranspiration in the April-September period on an average total of 306 mm rain for this period and 657.4 mm potential evapotranspiration).

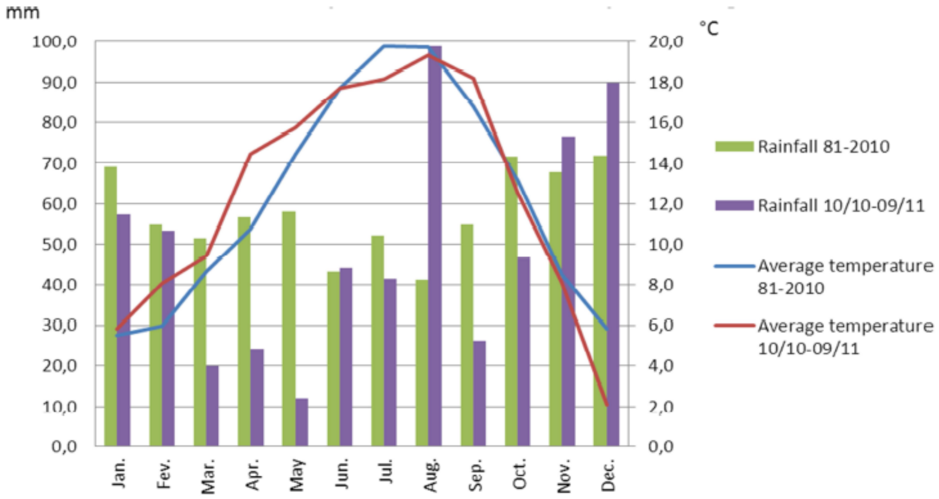

*Figure 15: main characteristics of the climate of production year 2010-2011*

The particularly low precipitations in spring may generate lower emissions to groundwater, and the higher temperatures can cause higher emissions to air than an average year. We performed a sensitivity analysis on these climatic inputs.

### 2.1.11 SOILS, ENVIRONMENT, AND YIELDS

Each plot presents a different type of soil, but quite similar slopes (3 to 6%). The soil layers were described by field observation with soil auger and soil analysis, and consolidated with comparison to existing detailed soil cartography of vineyard soils of the Middle Loire Valley. The soils characteristics were implemented in the PestLCI 2.0 soil database. Table 11 summarizes the soil characteristics of the 3 studied TMRs' plots.

*Table 11: soil and cover crop characteristics of the 3 TMR studied (TMR: technical management route, UTB: terroir base unit)*

| Case | Soil | slope% | cover crop extent | tillage |
|---|---|---|---|---|
| TMR 1 | UTB131 | 5 | 70% high density | no |
| TMR2 | UTB25 | 6 | 30%average density | no |
| TMR3 | UTB35 | 3 | 50%average density | no |

Soil characteristics and tillage should play a role on emissions to groundwater by changes in soil porosity. Slope and drainage should influence emissions to surface water, as should cover crop extent, and the latter should additionally influence emissions to air by changes in canopy area. The sensitivity analyses will explore the influence of soil, slope, tillage, and cover-crop extent parameters on the results.

No surface water body lies at less than 100 m from the parcels. The plots are not drained. They are all cover-cropped but the covers present different densities and extents. Irrigation is not allowed in PDO vineyards under Middle Loire Valley climate; hence the studied plots are not irrigated (irrigation water would have to be added to rainfall, and thus increase surface water emission rate).

The yields for 2011 were the following: TMR1: 8000 kg grapes/ha; TMR2: 5250 kg grapes/ha; and TMR3: 7500 kg grapes/ha.

### 2.1.12 VINEYARD PROTECTION PROGRAMS

For each TMR, different spraying equipment and active substances were used by the growers (see Table S9 in the Supplementary material). Defining which of the 9 sprayers added to PestLCI 2.0 is most similar to the sprayers used by the growers was done through discussion with S. Codis, (pers. comm., 2014). Since the chosen sprayer type determines pesticide drift, which may influence the modelled emissions to air, the choice of sprayer type is included in the scenario uncertainty analysis.

## 2.2 SENSITIVITY ANALYSES

Two types of sensitivity analyses were carried out in order to identify the parameters towards which the outcomes of our customized version of PestLCI 2.0 are most sensitive, and hence which parameters should be focused on to reduce uncertainty caused by inventory work and landscape parameters documentation in future studies. Input parameter sensitivity (on quantitative parameters) and scenario sensitivity analysis (on qualitative parameters) were conducted.

The input parameter sensitivity analysis was carried out for the application of Folpet in TMR 1. Folpet was chosen for this analysis, because it is the organic PAI the most frequently used in viticulture in France (Ambiaud 2012b). As can be seen from table S12 in the supplementary material, in TMR 1 Folpet is applied in May using a recycling tunnel. The vineyard measures 100x100 meter, the soil of UTB 131 has a slope of 5% and it not drained. There is no surface water near the vineyard; therefore runoff of dissolved pesticide is classified as an emission to agricultural soil. The climate used to model this scenario was Blaison-Gohier’s. Starting from this basis scenario, 37 parameters were, one at a time, increased with 10%. These parameters include direct inputs that can be modified by PestLCI 2.0 users, as well as parameters included in the model’s climate and soil profiles and properties of the active ingredient. Each parameter was changed with the same percentage in order to allow for a comparison of the sensitivities of the different parameters. For each change in input parameter, the emissions to air, agricultural soil and groundwater were calculated. Finally the percentages of change in the emissions were calculated. Since the aim of this assessment is to focus on the inventory data collection, rather than determining the sensitivities of the final results, this sensitivity assessment was carried out for 1 active ingredient.

The scenario sensitivity analysis was conducted on the inputs that involve discrete data, i.e. type of sprayer, of soil or climatic datasets. The effects of input change on the model outputs were assessed in terms of percentage of variation of the output in comparison to a reference case. The tested input types were assessed on basis of the same PAIs application event, by varying one parameter at a time. A reference case was chosen for each input type (Table 12). For example: the tunnel sprayer was taken as the reference sprayer, the emissions found for the other sprayers were expressed as a negative or positive change of the emissions, expressed in a percentage, compared to the emissions calculated with the tunnel sprayer.

*Table 12: Tested input types for scenario uncertainty analysis, reference characteristics and number of alternatives tested.(PAI: pesticide active ingredient)*

| tested input "type" | Reference | PAIs | Month | alternatives tested |
|---|---|---|---|---|
| Weeding booms | PestLCI1 Soil Incorporation | Aclonifen | March | IMAG conv boom bare soil, IMAG conv boom cereals |
| Sprayers | Tunnel sprayer | Folpet | May | sprayer idk, sprayer spider vault, sprayer CG pneumatic, sprayer abmost pneumatic, sprayer GRV fantip, sprayer GRV AVI air assisted, sprayer GRV Avi non air assisted, sprayer pendillard TVI, sprayer crossflow fruit |
| Interception by mixed canopies | Vine 0 0%grass | Folpet | March | Vines 0 - w30% grass, Vines 0 - h30% grass, Vines I - a0% grass, Vines I - w50% grass, Vines 0 - h80% grass, Vines II - a0% grass, Vines II - w100% grass |
| Soils | UTB 131 | Folpet | March | UTBs 11, 25, 35, 156 |
| Tillage | No Tillage | Folpet | March | tillage |
| Months | March | Folpet | March | April, May, June, July, August |
| Climatic dataset | Oct. 2010: Sept. 2011 | Full program (11 PAIs) | March: July | 10/2009-9/2010; 10/2011-9/2012;<br>average of the 3 years10/2009-9/2012;<br>30 year average 1981-2010 Beaucouzé |

# 3 RESULTS

## 3.1 CASE STUDY: EMISSIONS OF ORGANIC PAI.S AND FWETOX

### 3.1.1 WITH PEST-LCI 2.0

Emissions were calculated by PestLCI 2.0 for every organic substance application done in 2011 for the 3 TMRs. Inorganic PAIs were excluded from the calculation, since they fall outside the scope of PestLCI 2.0.

The emission fractions vary to a large extent. These variations are determined by the PAIs' properties as well as parcel and application conditions (Figure 16).

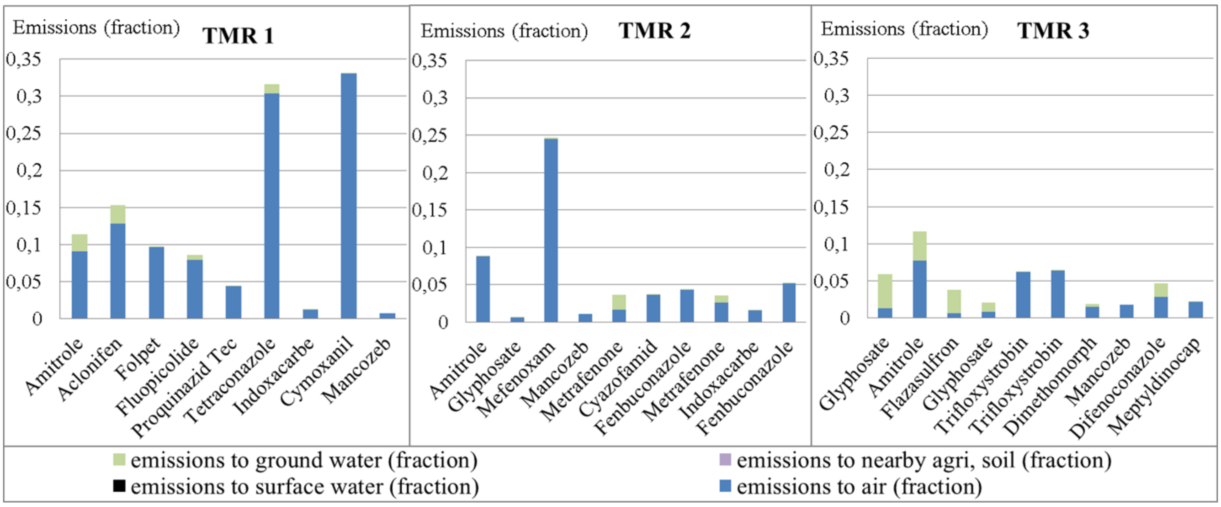

*Figure 16:(a, b, c): fraction of applied PAIs emitted in the 4 compartments presented in the chronologic order of application during 2011 cultivation year*

They do not exceed 0.35, and are lower than 0.15 for most of the PAI applications. They are highly dominated by air emissions, followed by ground water emissions. Emissions to nearby agricultural soil are negligible (from $2{\cdot}10^{-20}$ to $2{\cdot}10^{-4}$) and thus not visible on the charts. The absence or quasi-absence of freshwater emissions can be explained by the absence of water body around the parcels.

The three fungicides Tetraconazole, Cymoxanil and Mefenoxam were found to have the highest emissions, followed by two herbicides (Aclonifen and Amitrole).

For a same PAI, e.g. Amitrole, sprayed in all 3 TMRs, with the same type of boom, and on the same canopy (grass), emissions to air and to groundwater vary because of different soil and climatic conditions. These drivers are explored in the sensitivity analyses section.

High emissions fractions do not necessarily lead to high emissions: for most of the PAIs, high emissions are compensated by very low application doses (Cymoxanil, Tetraconazole), leading to moderate emissions quantities (Figure 17).

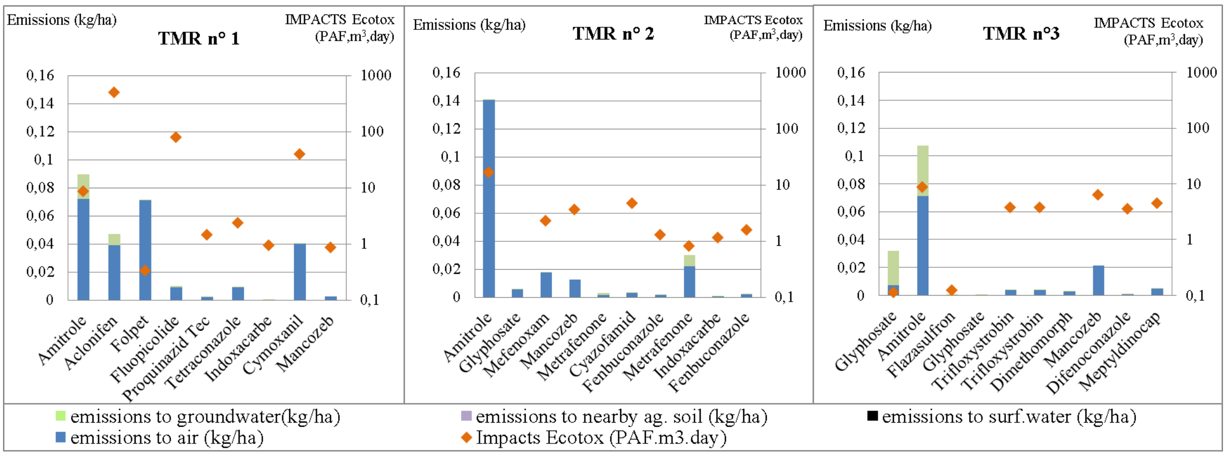

*Figure 17 (a, b, c):Quantities of PAIs emitted and per ha of vineyard in the 4 compartments and FwEtox calculated by USETox TM (note the log scale for TMR1 impacts FwEtox) in the chronologic order of application during the 2011 cultivation year; PAF : potentially affected fraction.*

The quantity of PAIs emitted per application is not higher than 0.14kg/ha in all scenarios. As was the case for the emission fractions, the emissions quantities are dominated by air emissions. Due to the combination of a large quantities applied (around 1kg/ha) and high emission fractions, Amitrole dominates the emissions to air in the three TMRs. After Amitrole, Folpet and Aclonifen show the highest emissions. In contrast, for Mancozeb, though applied at high rates, moderate emissions are observed due to low emission fractions.

FwEtox calculated applying USEtox™ CFs (Figure 17) reveals high differences for the different applications, due to high disparities in ecotoxicological profiles of the PAIs. The FwEtox of TMR1 is dominated by Aclonifen (500 PAF·m$^3$·day), Fluopicolide (80 PAF·m$^3$·day) and Cymoxanil (40 PAF·m$^3$·day). The other TMRs show much lower FwEtox than TMR 1.

Multiple factors differentiate the case vineyards TMR1, 2 and 3. The main factors are considered to be soil characteristics, sprayer equipment used and type of pesticides applied. TMR1 shows higher emission fractions than TMR3; however the total mass of emitted pesticide is lower because of the low doses applied for some substances. TMRs 2 and 3 show a much lower total FwEtox (33 and 37 PAF·m$^3$·day) than TMR1 (634 PAF·m$^3$·day), mainly due to the high ecotoxicity of Aclonifen used in TMR 1, even if this PAI is applied via sheltered boom, limiting wind drift. The comparison between the three TMRs discussed here considers only organic PAIs, even though inorganic substances are also involved in these three vine protection strategies but could not be assessed.

### 3.1.2 COMPARISON OF PESTLCI 2.0 RESULTS WITH TWO SIMPLIFIED MODELLING APPROACHES OF EMISSION QUANTIFICATION

The Ecoinvent approach applied for pesticides assumes that 100% of the applied pesticide is emitted to the soil (Nemecek and Schnetzer 2011), thus the agricultural soil is considered part of the ecosphere.(Neto et al. 2012) in their LCA of Portuguese wine Vinho Verde propose a substance generic partition as with 75 % of pesticides emitted to soil and 25% to the air. The results between the three approaches were compared on TMR 1 to 3 organic pesticides application program (Figure 18).

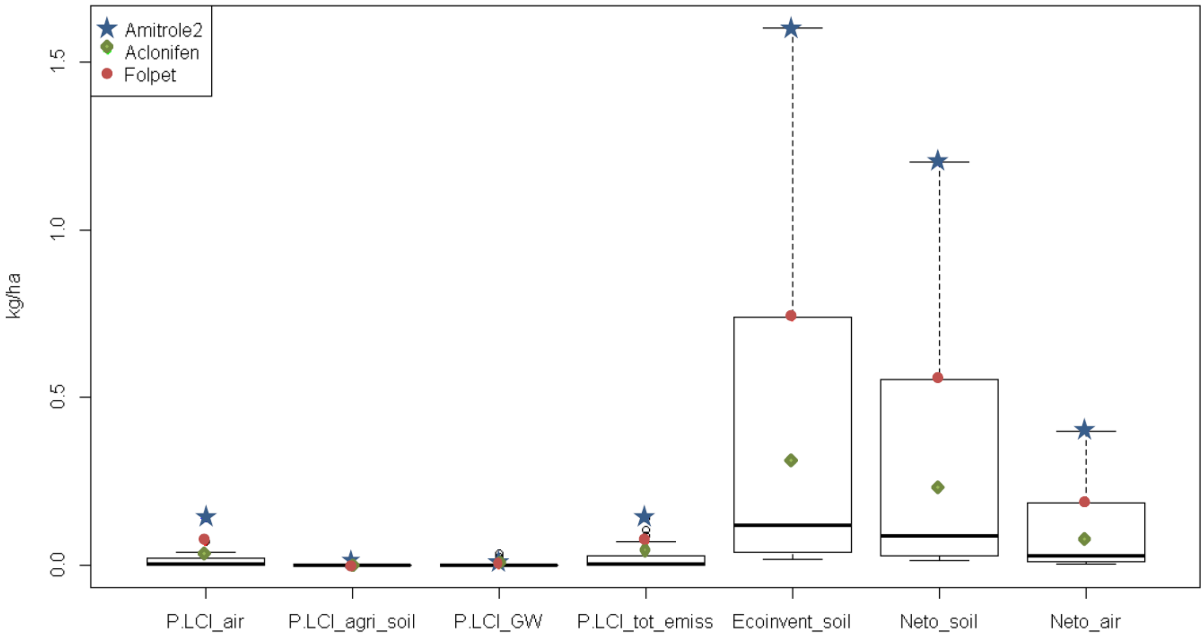

*Figure 18: Comparison of PAI emissions and their distribution calculated on the 3 plots vineyard protection programs (organic PAIs) by PestLCI 2.0, Ecoinvent and Neto et al. (2012) approaches.*

*Each boxplot shows the median of all values (bold line) flanked by the first (bottom) and the third (top) quartiles (limits of the box) and 1rst (bottom) and 9th (top) deciles (whiskers), outliers are plotted as individual points; 3 major contributing PAIs are illustrating the differences (colour points)*

As the results are not normally distributed, means and standard deviation cannot be used; results are thus compared through their medians and their distribution.

In the present study, the median of total emission fraction modelled with PestLCI 2.0 is 26 times lower than the total emission fractions estimated by the Ecoinvent and Neto et al. (2012) approaches (Neto et al., 2012 total emissions= 25%air+75%soil=100%= Ecoinvent soil emissions). The median of PestLCI 2.0 modelled emission fraction to air is 7 times lower than the total emission fraction to air estimated by the Neto et al. (2012) approach.

This leads to huge differences in FwEtox estimates (USEtoxTM CFs applied in all cases) (

Figure 19): 32 times lower with PestLCI model than Ecoinvent and 36 times lower than Neto et al. (2012) approach.

Very high variability in FwEtox results within each of the three approaches must be noticed, which can be explained by large differences in the PAIs' CFs.

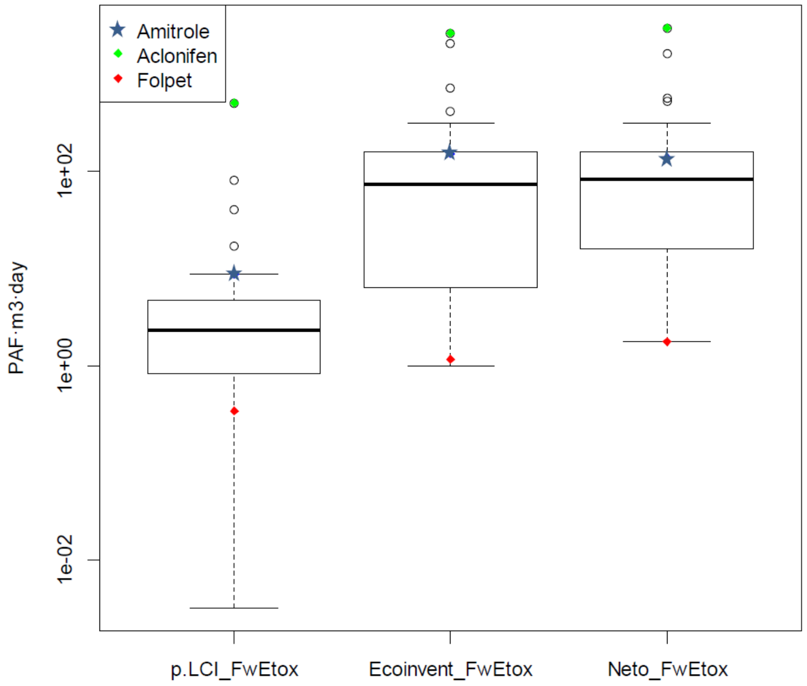

*Figure 19: Comparison of FwEtox calculated on the 3 TMR's vineyard protection programs emissions (organic PAIs) with USETox$^{TM}$ CFs (logarithmic scale).*

*Each boxplot shows the median of all values (bold line) flanked by the first (bottom) and the third (top) quartiles (limits of the box) and 1rst (bottom) and 9th (top) deciles (whiskers), outliers are plotted as individual points; 3 major contributing PAIs are illustrating the differences (colour points)*

The emission quantities of individual PAIs that are estimated by PestLCI 2.0 are always lower than the substance generic approaches estimates (Figure 20).

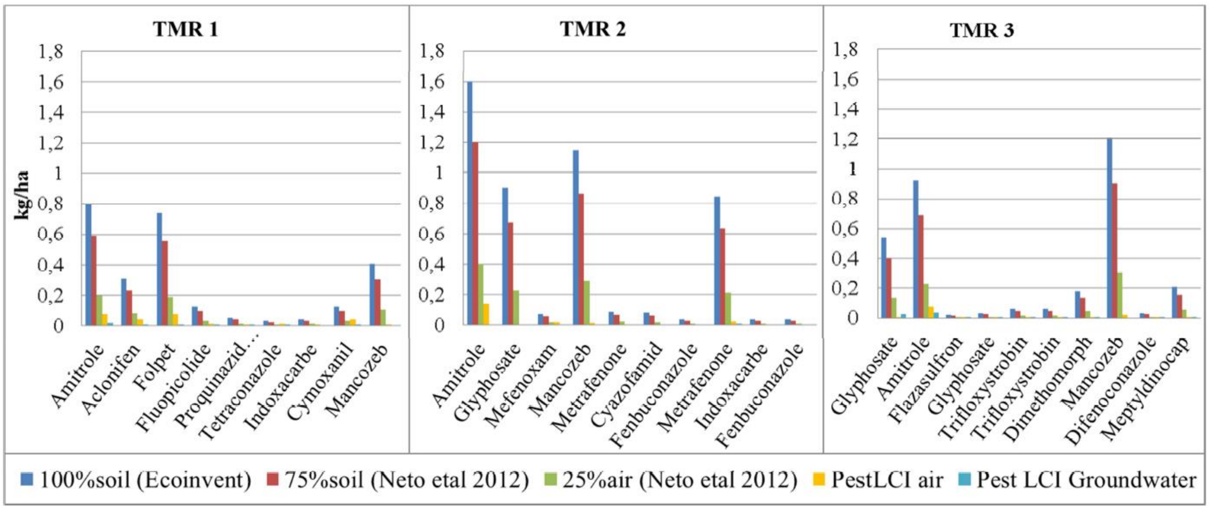

*Figure 20: (a, b, c): comparison of emissions per ha treated from PestLCI 2.0 and two simplified emission modelling approaches.*

The PestLCI approach results in total emissions that are between 3 (Cymoxanil, TMR1) and 143 (Glyphosate, TMR2) times lower than the 100% emitted to soil approach (Ecoinvent). PestLCI emissions to air are between 0.75 (Cymoxanil, TMR1) and 42 (Flazasulfuron, TMR3) times lower than Neto et al. (2012) approach. Moreover, the ranking of the PAIs on basis of their FwEtox is not the same between PestLCI 2.0 and the two substance generic approaches.

## 3.2 SENSITIVITY ANALYSIS

### 3.2.1 SENSITIVITY OF THE MODEL TO QUANTITATIVE INPUTS

The results for the sensitivity analysis are shown in Table 13. This table lists the 3 input parameters to which the emissions to air, surface water and ground water are most sensitive. The sensitivities of all tested parameters are found in table S13 in the supplementary material.

Table 13: *Summary of sensitivity analysis, showing sensitivities as the change in emissions (%) resulting from a 10% change in the given input parameter*.

| Parameter | Sensitivity (%) |
|---|---|
| $f_{air}{}^{1}$ | |
| solar irradiation | -3.0 |
| $T_{average}$ in the month of application | 2.2 |
| interception fraction | 0.99 |
| $f_{sw/ag.soil}{}^{1}$ | |
| interception fraction | -6.9 |
| field slope | 1.3 |
| soil half life | 1.1 |
| $f_{gw}{}^{1}$ | |
| interception fraction | 6.9 |
| soil solid matter fraction | 3.2 |
| soil water fraction | 2.1 |

1: Abbreviations used: $f_{air}$: emissions to air; $f_{sw/ag.soil}$: emissions to surface water/near-field agricultural soil; $f_{gw}$: emissions to ground water.

The emissions to air are mostly sensitive to parameters that determine pesticide presence on leaves like solar irradiation which affects the rate of degradation. Since degradation competes with volatilization, a change in the degradation rate affects the rate of volatilization. The average ambient temperature affects both the volatilization and degradation rate. The third most sensitive parameter was found to be the primary interception fraction, determining the pesticide distribution between leaves and soil. The choice of application method can be even more influential than the other parameters tested in Table 13, but, as a discrete choice, it was included in the scenario sensitivity analysis (see section 3.2.2). The emissions to nearby agricultural soil (or surface water, had that been present) are sensitive to parameters that determine how much pesticide is present on the soil surface such as the fraction of applied pesticide that is intercepted by leaves, and the soil half-life of the pesticide. Moreover, the slope of the field was shown to be an important parameter: the steeper a slope, the more rain water will start to run off. Finally, emissions to ground water were also found to be mostly sensitive towards the fraction of pesticide that initially reaches the soil, as well as towards soil properties.

### 3.2.2 SCENARIO SENSITIVITY ANALYSIS

The sensitivities of $f_{air}$, $f_{sw}$, $f_{gw}$ and FwEtox to the different inputs cited in section 2.2 were calculated by making each input vary in the range of values available in the model (Table 14).

Sensitivity analysis results of $f_{air}$ and FwEtox show a very strong correlation (see Fig. S1 in the Supplementary material) because $f_{air}$ is the major emission route in this case study. For this reason, only $f_{air}$ sensitivity results will be presented in the section below.

*Table 14: Highest variations of emission fractions in PestLCI 2.0 per input type (PAI: pesticide active ingredient, $f_{air}$: emissions to air; $f_{sw/ag.soil}$: emissions to surface water/near-field agricultural soil; $f_{gw}$: emissions to ground water)*

| Input type | Reference | PAIs | Highest variation $f_{air}$ in % | Highest variation $f_{sw}$ in %* | Highest variation $f_{gw}$ in % | Number of alternatives tested |
|---|---|---|---|---|---|---|
| Weeding booms | PestLCI 1 Soil Incorporation | Aclonifen | 4 | -0.53 | -0.53 | 2 |
| Sprayers | Tunnel sprayer | Folpet | 51 | No emissions | -5 | 9 |
| Interception by mixed canopies | Vine 0 0%grass | Folpet | 378 | -77 | -77 | 7 |
| Soils | UTB 131 | Folpet | 0.03 | -100 | -64 | 4 |
| Tillage | No tillage | Folpet | 0 | 0 | -87 | 2 |
| Months | March | Folpet | 43 | -63 | -73 | 5 |
| Climatic dataset | Oct. 2010: Sept. 2011 | 11 PAIs | 65 | NA | 443 | 3 |

* a freshwater water body was considered at 20m distance from parcel boundary, except for climatic dataset test

The most influential parameters on $f_{air}$ are the interception by the canopy (or canopies) and, to a lesser extent, the climatic annual dataset. Concerning $f_{gw}$, the main drivers turned out to be the climatic dataset (climatic year or climatic month).

A complementary sensitivity scenario analysis on 4 climatic dataset including averages on 30 years for a complete treatment program is available in the suppl. material, section S-E.

# 4 DISCUSSION AND OUTLOOK

## 4.1 CASE STUDY INSIGHTS

When using the original Usetox CFs for Folpet, the dominancy of Folpet found in the FwEtox results of the present case study is consistent with results obtained by(Vázquez-Rowe et al. 2012b) and(Villanueva-Rey et al. 2014a) with PestLCI 1.0, where FwEtox is found to be dominated by Terbuthylazine (which was not applied here, its use being forbidden in France since 2003) and Folpet. A comparison of the present TMRs FwEtox profiles (using the original Usetox CFs for Folpet ) with the results obtained by(Vázquez-Rowe et al. 2012b) with PestLCI 1.0 in Galician vineyards shows very good environmental performance of the present TMRs: TMR1's FwEtox is half of the lowest FwEtox mentioned by this author (Copper impacts removed). However, the version of PestLCI used by these authors is an older version and was not customized for viticulture, which can cause overestimates of the emissions. This may have caused overestimation of the emissions: the recycling tunnel sprayer used to apply Folpet results in emissions to air that are lower than other application methods available in PestLCI 1.0. Moreover, the emissions to surface water are in general found to be lower in PestLCI 2.0 than in PestLCI 1.0 (see for example Dijkman et al., (2012)). The new CFs that we have calculated for Folpet, and used in this paper yield a low FwEtox for this PAI and thus a lower FwEtox for TMR1.

Inorganic or partially inorganic PAIs could not be modelled here because of the lack of model appropriated to their specific physic-chemical behaviour; however, they were also applied to the case vineyards (see table S12 in the Supplementary material): one (TMR3) to five (TMR1) PAIs applications. The copper-based PAIs are particularly expected to further increase the FwEtox of the TMRs if included (Mackie et al. 2012; Vázquez-Rowe et al. 2012b). Their widespread use in viticulture reveals the need for models capable of quantifying inorganic PAIs emissions.

## 4.2 SENSITIVITY AND INVENTORY PRIORITIES

The results of the sensitivity analysis shown in Table 13 do not give the same hierarchy between the parameters as those presented by Dijkman et al. (2012). This can be explained by differences in active ingredients, soil, climate and pesticide application methods used as inputs between both studies. In addition, modelling of some of the fate modules in PestLCI have been modified, as described in (Dijkman 2014).

The sensitivity analyses show that climate, canopy interception and soil granulometry play major roles in the results of both PAI emissions and FwEtox. Therefore these parameters should, ideally, not be estimated by default or average values. Moreover, efforts should be put on main contributors to $f_{\text{air}}$, $f_{\text{sw}}$ and $f_{\text{ag.soil}}$ sensitivity because, in the current state of characterization methods, emissions to ground water are not taken into account for impacts calculation.

The importance of pesticide interception by plant and cover-crop canopies, especially on $f_{\text{air}}$, implies that width and density of grass cover strip as well as vine development stages must be well documented in viticulture.

The importance of the climatic dataset on emissions to $f_{\text{air}}$ and $f_{\text{gw}}$ points out the necessity to use the actual climatic dataset of a given year when one wants to assess a real TMR in that given year: the use of another climatic year or long-term average climatic data can introduce important uncertainty in the results.

The choice of soil type induces important variations in emissions to water $f_{sw}$ and $f_{gw}$, but causes very few changes in $f_{air}$. However, detailed soil description is time consuming and/or costly, hence not available for all vineyard situations.

Concerning the role of sprayer type in PestLCI 2.0, results of herbicides emissions are nearly not affected by the choice of weeding boom type; in contrast, the type of sprayer chosen for applications on vine canopy is the 3rd most important driver of $f_{air}$ variation.

## 4.3 COMPARISON TO SIMPLIFIED EMISSION/INVENTORY MODELLING APPROACHES

Large differences in emissions and impacts were found between the two simplified emission/inventory modelling approaches (Ecoinvent and Neto et al. 2012) and PestLCI 2.0-based emission quantification. The definition of system boundaries is shown to have considerable influence on a pesticide’s emissions quantification results (van Zelm et al. 2014; Dijkman et al. 2012). In the studies presented by(Nemecek and Schnetzer 2011; Neto et al. 2012; Petti et al. 2006b), soil (in general, including agricultural soil) is considered part of the ecosphere and all pesticides transfers to this compartment are considered emissions to the ecosphere. The PestLCI model, in contrast, considers the entire field parcel as part of the technosphere including the top 1 m soil and a 100 m air column above it (Dijkman et al. 2012; Birkved and Hauschild 2006), and models fate of chemicals within the technosphere and emissions to the ecosphere (Dijkman et al. 2013). This choice was done considering that agricultural fields are highly manipulated and controlled and therefore not ”natural”. Accounting for the sole emissions that cross the parcel borders is a first element limiting the quantity of emitted pesticides as modelled by PestLCI 2.0, compared to the other approaches tested. However that is not the only cause of lower emissions and FwEtox; considering processes of evaporation, runoff and leaching, including the actual properties of the PAIs applied, canopy influence, soils and sprayers all allows for a more accurate adjustment of estimates to the real phenomena. Degradation of PAIs and their uptake by the plants are actual processes that are not considered in the substance generic approaches tested, but accounted for in PestLCI 2.0.

A “100% emission to agricultural soil” assumption, as done in Ecoinvent, at first glance appears to be rather conservative (e.g. interception by the crop is completely neglected etc.). However, the available life cycle impact assessment (LCIA) methods (e.g. USE-LCA (van Zelm et al. 2009), CML 2002 (Guinee 2002) etc.) differ in their system boundaries and assumptions. Some of these LCIA methods model agricultural system-ecosphere transfers, the inventory just needs to quantify the amount of PAIs emitted from the sprayer. Ecoinvent 100% emissions to agricultural soil assumption is relevant in the case of these specific LCIA methods (Nemecek, personal communication 2014), nevertheless, site and applications techniques specific conditions influence the emissions cannot be accounted for applying this standard Ecoinvent emission quantification approach.

In the case of use of LCIA methods that do not model the transfer from agricultural system to ecosphere and degradation processes as USEToxTM, this “100% emissions to agricultural soil" assumption might lead, as shown in the present study, to the overestimation of impacts to soil or also to the underestimation to impacts in water and air. Thus the pesticide emission fractions need to be improved by the LCA practitioners on a case to case basis potentially taking into account dynamic issues which can't be handled by inventory databases. This assessor driven improvement of the pesticide emission profiles however is only in few (including the present case) performed. Further applying complex inventory models like PestLCI is a time and data demanding issue. However, neglecting e.g. crop interception will entail overestimation of the emission fractions and hence application of the conservative default pesticide emission profiles applied in Ecoinvent, as well as the approach used by Neto et al. (2012), will lead to an overestimation of the potential toxicity impacts induced by application of pesticides in most crop related LCAs. Comparing the approaches applied by Ecoinvent and Neto et al. (2012), would most likely reveal that the Ecoinvent approach is the least conservative of the two approaches due to the partial immobilization of pesticides in the soil compartment combined with the effective removal/fate processes taking place in this compartment.

It is obvious that the 3 compared approaches yield quite different results, which may appear peculiar. One might ask if some of the considered inventory approaches are over-/under-estimating the pesticide emissions. Apart from the already mentioned study by Dijkman et al (2013), little work seems to have been done in trying to answer this question, or the consequence of the different modelling approaches on freshwater ecotoxicity impacts. The question whether the inventory approaches studied here are over- or underestimating emission is hard if possible to answer at all, since the perception of whether the field or parts hereof belongs to the technosphere/ecosphere and hence what pesticide flows should be regarded elementary/non-elementary flows will in accordance with Hofstetter (1998) differ from assessor to assessor and hence differ depending on the way the assessor perceives the world. Since PestLCI, in line with Hofstetter (1998), considers the field as part of the technosphere, the fate processes occurring in the field are also taking place within the technosphere. Numerous fate processes take place within the technosphere (in relation to e.g. waste water treatment, bread baking, beer brewing processes etc.) however the fact that the in-field fate processes are handled by a pesticide dedicated fate model and not by a chemical generic characterization model is a distinctive feature of PestLCI.

## 4.4 FURTHER IMPROVEMENTS AND DEVELOPMENTS

PestLCI 2.0 could be improved by further developments in the modelling of airborne drift, which can be considerable (Jensen and Olesen 2014) but the complexity of the phenomena (Gil et al. 2008) and the lack of (generic) data are considered major obstacles for this improvement. More or less for the same reasons, pesticide metabolites are not accounted for in the present version of PestLCI 2.0. Accounting for application parameters as sprayers' speed, droplets size, temperature, relative humidity would be ideal for further refinement of the modelling of the spray mixture behaviour and fate, but these parameters are too difficult to obtain from the growers, and would further entail an even more complicated inventory.

(Dousset et al. 2010) found that a grass cover under vines permitted a two- to fourfold reduction of pesticides leaching to ground water in relation with increase of PAIs sorption in the soil thanks to organic matter content increase. This question couldn't be addressed here but should in the further developments of PestLCI 2.0.

High percentages of stones can be found in many vineyard soils, modifying water and solutes flow in the soil. These aspects could not be included in the present customization of PestLCI 2.0. However improvement of the way soil texture affects macropore transport in PestLCI 2.0 is recommended as an important issue to be considered in the coming PestLCI versions.

After the end of the vineyard life, the parcel can be bound to other uses and then can be considered coming back to ecosphere. The quantity of PAIs remaining in the soil after a given period (i.e. 30 or 40 years, when the vines typically are pulled out) is information that would be useful for estimating impacts of viticulture, in case of land use change. This information would be valuable inputs for soil quality indicators and could also be applied to land use changes related to agriculture in general.

The question of impacts of pesticides on the ecosystem present in the field, which is considered here as technosphere is a controversial question (van Zelm et al. 2014), especially because in integrated farming and organic farming, this ecosystem is considered as an ally against pests and disease and should be preserved as much as possible. However, according to ILCD (European Commission Joint Research Centre 2010), "Pesticide and fertilizer applications are no emission, but part of the product flows within the (man-managed) technosphere". Hence the question of effects of pesticides on internal ecosystems should be addressed in a different way e.g. by accounting for reduced ecosystem services by land use change (i.e. the transition from ecosphere to technosphere) or through specific biodiversity indicators.

In organic viticulture, sulfur and copper (inorganic PAIs) are the only means available to manage respectively powdery and downy mildew, and represent important quantities of applied pesticides in viticulture in general, especially sulfur. As previously mentioned, PestLCI 2.0 model is designed only for organic PAI emissions modelling. Thus, a comparison between conventional and organic viticulture or the inclusion of organically managed cases in a study can't be dealt with solely through PestLCI 2.0. In contrast to pesticides, ILCD (European Commission Joint Research Centre 2010) points out the fact that "some inputs to soil do not leave the technosphere via leaching etc., but are accumulated in the soil. The amount/…/ applied to the field is directly inventoried as emission to agricultural soil", the latter is also the case for copper used as pesticide in viticulture (Mackie et al. 2012) that should thus be inventoried as heavy metal. Nevertheless, the primary distribution should be calculated first, especially to quantify drifted copper to ecosphere. A model similar to PestLCI is needed for emissions modelling of other inorganic pesticides. Upon release inorganic chemicals undergo speciation (meaning that an e.g. copper emission to arable land simply can't be modelled as and emission of e.g. $Cu_2^+$, but should be modelled as a set of species ($CuOH^+$, $CuCl^+$, $CuCO_3$, $Cu_2^+$, $Cu^+$, $CuSO_4$ etc.). Many of such species do not degrade as organic chemicals do and the fate modelling of inorganic emission is typically focused on the removal of such species (via burial in sediments, leaching in soils etc.) from the part of the ecosphere, where interaction with biological receptors may occur (i.e. the part of the ecosphere where (eco)toxicological effects may occur). Modelling the behaviour of inorganic emissions to arable land hence demands a different approach than when modelling emissions of organic chemicals. These differences are so large that in order to model inorganic pesticides appropriately in PestLCI a range of new sub-models for inorganic chemicals would have to be developed for PestLCI.

An additional, however important, issue is whether the overall uncertainty improvements provided by highly specific/detailed inventory approaches such as PestLCI makes sense keeping in mind the considerable uncertainties related with other steps in LCA e.g. characterization of chemical emissions. We think that if any uncertainty aspect in LCA can be improved it should be improved irrespective of whether other steps in LCA currently can or can’t match such uncertainty improvements. LCA is still developing and chemical characterization in LCA will also at some point in time maturate (and thus move beyond consensus) in terms of uncertainty.

## 5 CONCLUSION

While having been intended mainly for arable crops, the PestLCI 2.0 inventory model, due to its rather flexible framework, has here been adapted for viticulture without compromising the model framework. The PestLCI 2.0 customized version for viticulture, presented in the paper at hand, facilitates the calculations of emission loads for vertically trained vineyards with a wide range of sprayers. It further provides a considerable, though non-exhaustive, PestLCI pesticide database update of viticulture specific PAIs, completed by the corresponding USEtox$^{TM}$ FwEtox CFs, and it allows taking into account cover crop effect on PAIs emissions. High variability of PAI emissions and FwEtox due to pesticides properties, spraying and environmental conditions and comparison with simplified emission modelling substance generic approaches of pesticides PAIs emissions quantification show the interest of substance- and conditions- specific modelling with PestLCI.

Finally, some of the new PestLCI model parameters can also be used for other perennial or bush crops as long as equipment, canopy shape and PAIs stay in the range of available options. Finally, some of the new PestLCI model parameters can also be used for other perennial or bush crops as long as equipment, canopy shape and PAIs stay in the range of available options.

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# SUPPLEMENTARY MATERIAL

## *Pesticides emissions modeling and freshwater ecotoxicity assessment for Grapevine LCA: adaptation of PestLCI 2.0 to viticulture*

Renaud-Gentié Christel, Dijkman Teunis J., Bjørn Anders, Birkved Morten

Table S1: Overview of changes made to PestLCI 2.0 for this project

| | | |
|---|---|---|
| **Pesticide active ingredients** | Ametoctradine, Amitrole, Benalaxyl-M, Benthiavalicarb, Boscalid, Carfentrazone ethyl, Cyazofamid, Cymoxanil, Difenoconazole, Fenbuconazole, Flazasulfron, Fludioxonil, Fluopicolide, Glufosinate ammonium, Indoxacarb, Mepanipyrim, Meptyldinocap, Mefenoxam, Metrafenone, Proquinazid, Pyraclostrobine, Pyrethrum, Quinoxifen, Spinosyn A and D, Spiroxamine, Tetraconazole, Triadimenol, Zoxamide<br>*An overview of the properties of the pesticides introduced to PestLCI 2.0 is presented in table S3.* | |
| **Climate** | Weather station | Climate profile |
| | - Beaucouzé<br>- Beaulieu-s-Layon<br>- Blaison-Gohier<br>- Fontaine-Guerin<br>- Martigne-Briand | For each of these 5 weather stations, the following climate profiles were introduced:<br>- October 2009-September 2010<br>- October 2010-September 2011<br>- October 2011-September 2012<br>- Average profile containing averaged monthly data for the period October 2009 to September 2012. |
| | - Beaucouzé | - 30 year average 1971-2000<br>- 30 year average 1981-2010 |
| | *A brief overview of the properties of the climate data introduced to PestLCI 2.0 is presented in table S5. Data has been obtained from Météo France, which did not give permission to publish this data.* | |
| **Soil profiles** | - UTB11<br>- UTB25<br>- UTB35<br>- UTB131<br>- UTB156<br>*A detailed description of the soil properties introduced into PestLCI 2.0 is given in table S6.* | |
| **Pesticide application method** | - Canon spider vault 8 rows<br>- CG pneumatic sprayer<br>- ABMOST pneumatic sprayer side<br>- GRV FanTip air-assisted sprayer<br>- GRV IDK air-assisted sprayer<br>- GRV AVI air-assisted<br>- GRV AVI non air-assisted<br>- Pendillard TVI non air-assisted<br>- Recycling tunnel<br>*The spray drift equations derived for these sprayers are listed in table S8.* | |

| **Input parameter** | Data added to PestLCI 2.0 | |
|---|---|---|
| **Distribution of pesticide between leaves (vine and grass) and soil** | The 4 development stages of vines present in PestLCI 2.0, required to calculate the distribution of pesticide between leaves and soil, were expanded to represent vineyards with various percentages of grass between the vines in various densities of grass cover, here indicated with l, a, h (low, average and high, respectively). In addition, a development stage 0 was added. | |
| | Vines 0<br>- 0% grass<br>- 30% grass, l and h<br>- 50% grass, l and h<br>- 80% grass, l and h<br>- 100% grass, l and h | Vines III<br>- 0% grass<br>- 30% grass, a<br>- 50% grass, a<br>- 80% grass, a<br>- 100% grass, a |
| | Vines I<br>- 0% grass<br>- 30% grass, a<br>- 50% grass, l and h<br>- 80% grass, l and h<br>- 100% grass, l and h | Vines IV<br>- 0% grass<br>- 30% grass, a<br>- 50% grass, a<br>- 80% grass, a<br>- 100% grass, a |
| | Vines II<br>- 0% grass<br>- 30% grass, a<br>- 50% grass, a<br>- 80% grass, l and h<br>- 100% grass, l and h | |
| **Freshwater presence** | In case freshwater was not present within 100 m from the vineyard under consideration, the pesticide present in runoff from the vineyard was considered an emission to the soil outside the vineyard. | |

## S-A) Pest, diseases and weeds management in viticulture

The main pests damaging the vine canopy are primarily the fungi downy mildew (Plasmopara Viticola) and powdery mildew (Uncinula Necator), which necessitate fungicide treatments. The other fungi and the main insect pests (moths, leafhoppers and phytophagous mites) are not systematically treated. Vineyard management includes also weed control, since weed presence can affect vine growth by competition for water and nutrients. Most of these pests require specific PAIs. The risk of resistance acquisition by the pests implies frequent change of PAIs, in conventional viticulture especially for PAIs presenting a single-site mode of action (i.e. acting against only one point on one metabolic pathway in a pathogen (McGrath M (2007)). Vineyard treatment programs therefore usually involve a variety of PAIs. This is however not the case in organic viticulture, where the fungicides used (primarily copper and/or sulfur based fungicides) have multi-site action, while weeds in organic viticulture are mechanically controlled.

## S-B) The case of Copper and sulfur fungicides

Conventional viticulture uses inorganic sulfur as one of several means to manage powdery mildew, but, in organic viticulture, sulfur is the only means available to manage powdery mildew. Similarly, copper, in various forms, is the main inorganic substance applied in the management of downy mildew. In conventional viticulture, copper is applied once or twice per season. Being the only mean available in organic vineyard management against dawny mildew, organic vineyards are on average treated more often with copper than conventional vineyards (European Council, 2007) leading to a higher soil copper annual load in organic vineyards compared to conventional ones.

**References :**

McGrath M (2007), What are fungicides? The plant health instructor, doi:10.1094/PHI-I-2004-0825-01

European-Council (2007) Council regulation (EC) No 834/2007 of 28 June 2007 on organic production and labelling of organic products and repealing regulation (EEC) Council Regulation (EC) No 834/2007, vol L 189/1. Official Journal of the European Communities.

Table S2: Active ingredients listed in the study

*Grey box: the inorganic and partially inorganic PAIs that could not be assessed using PestLCI 2.0;*

*a ▪ indicates a compound for which a new CF was calculated, using USETox*$^{TM}$

| | Name of the pesticide active ingredient | Type | CAS no. |
|---|---|---|---|
| ▪ | Ametoctradine | Fungicide | 865318-97-4 |
| | Amitrole (= Aminotriazole) | Herbicide | 61-82-5 |
| ▨▪ | Ammonium thiocyanate (Ammonium sulfocyanate) | Insecticide | 001762-95-4 |
| ▪ | Benthiavalicarbe | Fungicide | 413615-35-7 |
| ▪ | Benalaxyl-M | Fungicide | 98243-83-5 |
| ▨▪ | Bordeaux mixture | Fungicide | 8011-63-0 |
| ▪ | Boscalid (510) | Fungicide | 188425-85-6 |
| | Carfentrazone-ethyl | Herbicide | 128639-02-1 |
| ▨ | Copper (II) variant copper hydroxide | Fungicide | 20427-59-2 |
| ▨ | Copper (II) variant copper oxychloride | Fungicide | 1332-65-6 or1332-40-7 |
| ▨ | Copper (II) variant tribasic copper sulfate | Fungicide | 12527-76-3 |
| ▨ | Copper (I) oxide, | Fungicide | 1317-39-1 |
| ▪ | Cyazofamid | Fungicide | 120116-88-3 |
| | Cymoxanil | Fungicide | 57966-95-7 |
| | Difenoconazole | Fungicide | 119446-68-3 |
| ▨ | Disodium phosphonate | Fungicide | 13708-85-5 |
| | Fenbuconazole (=IDM) | Fungicide | 114369-43-6 |
| ▪ | Flazasulfron | Herbicide | 104040-78-0 |
| | Fludioxonil | Fungicide | 131341-86-1 |
| ▪ | Fluopicolide | Fungicide | 239110-15-7 |
| | Glufosinate-ammonium | Herbicide | 77182-82-2 |
| | Indoxacarbe (=DPX MP062 ) | Insecticide | 173584-44-6 |
| | Méfénoxam (= Metalaxyl-m) | Fungicide | 70630-17-0 |
| ▪ | Mepanipyrim | Fungicide | 110235-47-7 |
| ▪ | Meptyldinocap | Fungicide | 131-72-6 |
| ▪ | Metrafenone (=AC 375839) | Fungicide | 220899-03-6 |
| ▪ | Proquinazid technique | Fungicide | 189278-12-4 |
| ▪ | Pyraclostrobine | Fungicide | 175013-18-0 |
| | Pyrethrins (= Pyrethrum) | Insecticide | 8003-34-7 |
| ▪ | Quinoxyfen | Fungicide | 124495-18-7 |
| ▪ | Spinosad (= a mix of Spinosyn A and D) | Insecticide | 168316-95-8 |
| | Spinosyn A | Insecticide | 131929-60-7 |
| | Spinosyn D | Insecticide | 131929-63-0 |
| ▪ | Spiroxamine | Fungicide | 118134-30-8 |
| ▨▪ | Sulfur | Fungicide/acaricide | 7704-34-9 |
| ▪ | Tetraconazole | Fungicide | 112281-77-3 |
| | Triadimenol | Fungicide | 55219-65-3 |
| ▪ | Zoxamide | Fungicide | 156052-68-5 |
| | Aclonifen | Already included in PestLCI 2.0 (herbicide) | |
| | Azoxystrobine | Already included in PestLCI 2.0 (fungicide) | |
| | Cyprodinyl | Already included in PestLCI 2.0 (fungicide) | |
| | Diméthomorphe | Already included in PestLCI 2.0 (fungicide) | |
| | Fluazinam | Already included in PestLCI 2.0 (fungicide) | |
| | Folpet | Already included in PestLCI 2.0 (fungicide) | |
| ▨ | Fosetyl-aluminium | Already included in PestLCI 2.0 (fungicide) | |
| | Glyphosate | Already included in PestLCI 2.0 (herbicide) | |
| | Kresoxim-méthyl | Already included in PestLCI 2.0 (fungicide) | |
| | Mancozeb | Already included in PestLCI 2.0 (fungicide) | |
| | Metirame (= Metirame-zinc = Zineb) | Already included in PestLCI 2.0 (fungicide) | |
| | Tebuconazole | Already included in PestLCI 2.0 (fungicide) | |
| ▪ | Trifloxystrobine | Already included in PestLCI 2.0 (fungicide) | |

**S-C) Sources used for pesticides chemical properties for introduction in Pest LCI 2.0:**

e-phy (MAAF and ONPV 2013) for correspondence between commercial name and active substance, PPDB (University-of-Hertfordshire 2013), TOXNET (US-National-Library-of-Medicine 2013) and Chemspider (Royal-Society-of-Chemistry 2013) for main chemical and physical characteristics. Data gaps were compensated for applying the QSAR included in the EPI Suite$^{TM}$ (US-Environmental-protection-Agency 2012). The physical-chemical and fate properties of the PAIs originated in living organisms (Pyrethrum, Spinosyn) were found in BPDB (University-of-Hertfordshire 2012) and some of the previously cited databases.

**References** :

e-phy, Le catalogue des produits phytopharmaceutiques et de leurs usages des matières fertilisantes et des supports de culture homologués en France (2013) Ministère de l'Agriculture, de l'Agroalimentaire et de la Forêt, Organisation Nationale pour la Protection des Végétaux. http://e-phy.agriculture.gouv.fr/. Accessed october-december 2013 and january 2014

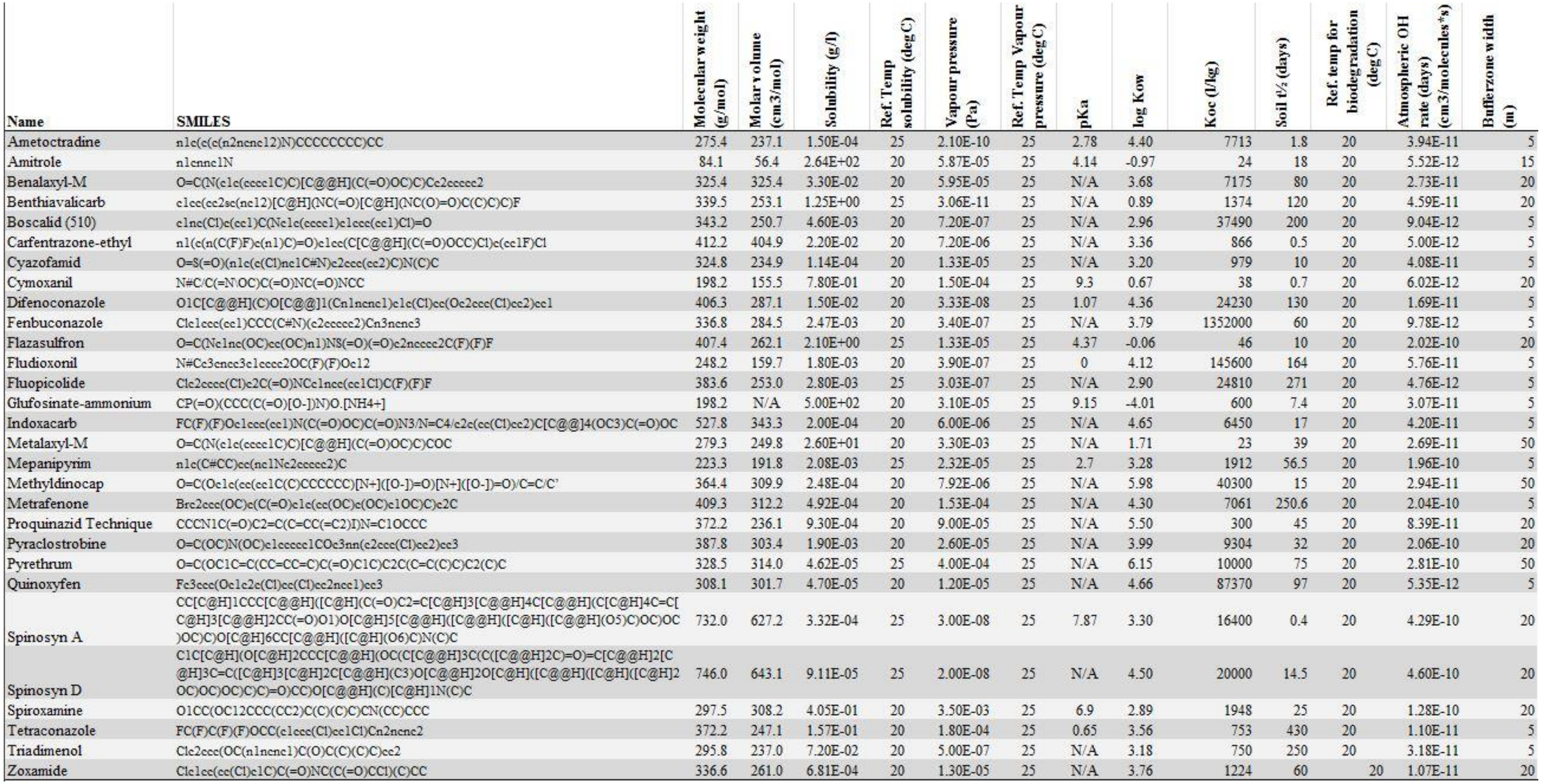
The Bio-Pesticide DataBase (BPDB) developed by the Agriculture & Environment Research Unit (AERU), (2012) University-of-Hertfordshire 2012 Accessed october-december 2013-january 2014

The Pesticide Properties DataBase (PPDB) developed by the Agriculture & Environment Research Unit (AERU), (2013) University-of-Hertfordshire 2006 - 2013.

US-Environmental-protection-Agency (2012) EPI SuiteTM v4.11. US Environmental protection Agency,

TOXNET - Databases on toxicology, hazardous chemicals, environmental health, and toxic releases. (2013) US national library of medicine. Accessed october-december 2013 and january 2014

Table S3: Properties of pesticides active ingredients newly introduced in PestLCI 2.0 (N/A = not applicable) bufferzone width determined for use on vineyards



| Name | SMILES | Molecular weight (g/mol) | Molar volume (cm3/mol) | Solubility (g/l) | Ref. Temp solubility (deg C) | Vapour pressure (Pa) | Ref. Temp Vapour pressure (deg C) | pKa | log Kow | Koc (l/kg) | Soil t½ (days) | Ref. temp for biodegradation (deg C) | Atmospheric OH rate (days) (cm3/molecules*s) | Bufferzone width (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ametoctradine | n1c(c(c(n2ncnc12)N)CCCCCCCC)CC | 275.4 | 237.1 | 1.50E-04 | 25 | 2.10E-10 | 25 | 2.78 | 4.40 | 7713 | 1.8 | 20 | 3.94E-11 | 5 |
| Amitrole | n1cnnc1N | 84.1 | 56.4 | 2.64E+02 | 20 | 5.87E-05 | 25 | 4.14 | -0.97 | 24 | 18 | 20 | 5.52E-12 | 15 |
| Benalaxyl-M | O=C(N(c1c(cccc1C)C)[C@@H](C(=O)OC)C)Cc2ccccc2 | 325.4 | 325.4 | 3.30E-02 | 20 | 5.95E-05 | 25 | N/A | 3.68 | 7175 | 80 | 20 | 2.73E-11 | 20 |
| Benthiavalicarb | c1cc(cc2sc(nc12)[C@H](NC(=O)[C@H](NC(O)=O)C(C)C)C)F | 339.5 | 253.1 | 1.25E+00 | 25 | 3.06E-11 | 25 | N/A | 0.89 | 1374 | 120 | 20 | 4.59E-11 | 20 |
| Boscalid (510) | c1nc(Cl)c(cc1)C(Nc1c(cccc1)c1ccc(cc1)Cl)=O | 343.2 | 250.7 | 4.60E-03 | 20 | 7.20E-07 | 25 | N/A | 2.96 | 37490 | 200 | 20 | 9.04E-12 | 5 |
| Carfentrazone-ethyl | n1(c(n(C(F)F)c(n1)C)=O)c1cc(C[C@@H](C(=O)OCC)Cl)c(cc1F)Cl | 412.2 | 404.9 | 2.20E-02 | 20 | 7.20E-06 | 25 | N/A | 3.36 | 866 | 0.5 | 20 | 5.00E-12 | 5 |
| Cyazofamid | O=S(=O)(n1c(c(Cl)nc1C#N)c2ccc(cc2)C)N(C)C | 324.8 | 234.9 | 1.14E-04 | 20 | 1.33E-05 | 25 | N/A | 3.20 | 979 | 10 | 20 | 4.08E-11 | 5 |
| Cymoxanil | N#C/C(=N\OC)C(=O)NC(=O)NCC | 198.2 | 155.5 | 7.80E-01 | 20 | 1.50E-04 | 25 | 9.3 | 0.67 | 38 | 0.7 | 20 | 6.02E-12 | 20 |
| Difenoconazole | O1C[C@@H](C)O[C@@]1(Cn1ncnc1)c1c(Cl)cc(Oc2ccc(Cl)cc2)cc1 | 406.3 | 287.1 | 1.50E-02 | 20 | 3.33E-08 | 25 | 1.07 | 4.36 | 24230 | 130 | 20 | 1.69E-11 | 5 |
| Fenbuconazole | Clc1ccc(cc1)CCC(C#N)(c2ccccc2)Cn3ncnc3 | 336.8 | 284.5 | 2.47E-03 | 20 | 3.40E-07 | 25 | N/A | 3.79 | 1352000 | 60 | 20 | 9.78E-12 | 5 |
| Flazasulfron | O=C(Nc1nc(OC)cc(OC)n1)NS(=O)(=O)c2ncccc2C(F)(F)F | 407.4 | 262.1 | 2.10E+00 | 25 | 1.33E-05 | 25 | 4.37 | -0.06 | 46 | 10 | 20 | 2.02E-10 | 20 |
| Fludioxonil | N#Cc3cncc3c1cccc2OC(F)(F)Oc12 | 248.2 | 159.7 | 1.80E-03 | 20 | 3.90E-07 | 25 | 0 | 4.12 | 145600 | 164 | 20 | 5.76E-11 | 5 |
| Fluopicolide | Clc2cccc(Cl)c2C(=O)NCc1ncc(cc1Cl)C(F)(F)F | 383.6 | 253.0 | 2.80E-03 | 25 | 3.03E-07 | 25 | N/A | 2.90 | 24810 | 271 | 20 | 4.76E-12 | 5 |
| Glufosinate-ammonium | CP(=O)(CCC(C(=O)[O-])N)O.[NH4+] | 198.2 | N/A | 5.00E+02 | 20 | 3.10E-05 | 25 | 9.15 | -4.01 | 600 | 7.4 | 20 | 3.07E-11 | 5 |
| Indoxacarb | FC(F)(F)Oc1ccc(cc1)N(C(=O)OC)C(=O)N3/N=C4/c2c(cc(Cl)cc2)C[C@@]4(OC3)C(=O)OC | 527.8 | 343.3 | 2.00E-04 | 20 | 6.00E-06 | 25 | N/A | 4.65 | 6450 | 17 | 20 | 4.20E-11 | 5 |
| Metalaxyl-M | O=C(N(c1c(cccc1C)C)[C@@H](C(=O)OC)C)COC | 279.3 | 249.8 | 2.60E+01 | 20 | 3.30E-03 | 25 | N/A | 1.71 | 23 | 39 | 20 | 2.69E-11 | 50 |
| Mepanipyrim | n1c(C#CC)cc(nc1Nc2ccccc2)C | 223.3 | 191.8 | 2.08E-03 | 25 | 2.32E-05 | 25 | 2.7 | 3.28 | 1912 | 56.5 | 20 | 1.96E-10 | 5 |
| Methyldinocap | O=C(Oc1c(cc(cc1C(C)CCCCCC)[N+]([O-])=O)[N+]([O-])=O)/C=C/C' | 364.4 | 309.9 | 2.48E-04 | 20 | 7.92E-06 | 25 | N/A | 5.98 | 40300 | 15 | 20 | 2.94E-11 | 50 |
| Metrafenone | Brc2ccc(OC)c(C(=O)c1c(cc(OC)c(OC)c1OC)C)c2C | 409.3 | 312.2 | 4.92E-04 | 20 | 1.53E-04 | 25 | N/A | 4.30 | 7061 | 250.6 | 20 | 2.04E-10 | 5 |
| Proquinazid Technique | CCCN1C(=O)C2=C(C=CC(=C2)I)N=C1OCCC | 372.2 | 236.1 | 9.30E-04 | 20 | 9.00E-05 | 25 | N/A | 5.50 | 300 | 45 | 20 | 8.39E-11 | 20 |
| Pyraclostrobine | O=C(OC)N(OC)c1ccccc1COc3nn(c2ccc(Cl)cc2)cc3 | 387.8 | 303.4 | 1.90E-03 | 20 | 2.60E-05 | 25 | N/A | 3.99 | 9304 | 32 | 20 | 2.06E-10 | 20 |
| Pyrethrum | O=C(OC1C=C(CC=CC=C)C(=O)C1C)C2C(C=C(C)C)C2(C)C | 328.5 | 314.0 | 4.62E-05 | 25 | 4.00E-04 | 25 | N/A | 6.15 | 10000 | 75 | 20 | 2.81E-10 | 50 |
| Quinoxyfen | Fc3ccc(Oc1c2c(Cl)cc(Cl)cc2ncc1)cc3 | 308.1 | 301.7 | 4.70E-05 | 20 | 1.20E-05 | 25 | N/A | 4.66 | 87370 | 97 | 20 | 5.35E-12 | 5 |
| Spinosyn A | CC[C@H]1CCC[C@@H]([C@H](C(=O)C2=C[C@H]3[C@@H]4C[C@@H](C[C@H]4C=C[C@H]3[C@@H]2CC(=O)O1)O[C@H]5[C@@H]([C@@H]([C@H]([C@@H](O5)C)OC)OC)OC)C)O[C@H]6CC[C@@H]([C@H](O6)C)N(C)C | 732.0 | 627.2 | 3.32E-04 | 25 | 3.00E-08 | 25 | 7.87 | 3.30 | 16400 | 0.4 | 20 | 4.29E-10 | 20 |
| Spinosyn D | C1C[C@H](O[C@H]2CCC[C@@H](OC(C[C@@H]3C(C([C@@H]2C)=O)=C[C@@H]2[C@H]3C=C([C@H]3[C@H]2C[C@@H](C3)O[C@@H]2O[C@H]([C@@H]([C@H]([C@H]2OC)OC)OC)C)C)=O)CC)O[C@@H](C)[C@H]1N(C)C | 746.0 | 643.1 | 9.11E-05 | 25 | 2.00E-08 | 25 | N/A | 4.50 | 20000 | 14.5 | 20 | 4.60E-10 | 20 |
| Spiroxamine | O1CC(OC12CCC(CC2)C(C)(C)C)CN(CC)CCC | 297.5 | 308.2 | 4.05E-01 | 20 | 3.50E-03 | 25 | 6.9 | 2.89 | 1948 | 25 | 20 | 1.28E-10 | 20 |
| Tetraconazole | FC(F)C(F)(F)OCC(c1ccc(Cl)cc1Cl)Cn2ncnc2 | 372.2 | 247.1 | 1.57E-01 | 20 | 1.80E-04 | 25 | 0.65 | 3.56 | 753 | 430 | 20 | 1.10E-11 | 5 |
| Triadimenol | Clc2ccc(OC(n1ncnc1)C(O)C(C)(C)C)cc2 | 295.8 | 237.0 | 7.20E-02 | 20 | 5.00E-07 | 25 | N/A | 3.18 | 750 | 250 | 20 | 3.18E-11 | 5 |
| Zoxamide | Clc1cc(cc(Cl)c1C)C(=O)NC(C(=O)CCl)(C)CC | 336.6 | 261.0 | 6.81E-04 | 20 | 1.30E-05 | 25 | N/A | 3.76 | 1224 | 60 | 20 | 1.07E-11 | 20 |

## S-D) Calculation of interception factors

The interception factor $f_l$ (pesticide deposition on leaves and truncs) for vine at development stage 0 has been estimated to 0.1, based on the orchard dormancy stage interception factor (0.2) given by Linders et al. (2000) after a division by 2 supposed to resemble the differences of perennial parts importance between fruit trees and vines.

**Details of calculation of interception factors for mixed canopies:**

As PestLCI 2.0 calculates the quantity of drifted pesticide on the basis of the dose applied and before calculating leaf interception, we decided to apply a drift quantity correction ratio based on the pesticide fraction going to air $F_{air}$ (this fraction comprises the fraction drifted $f_d$ and the fraction that volatilizes during spraying. In other words, it is the fraction that is not found on leaves and soil). It was deducted from the work of Sinfort et al 2009 and Sinfort 2014 and Codis et al. 2014 and calculated as $F_{air} = 1-(F_{soil} + F_{vine})$ with $F_{soil}$ and $F_{vine}$ = fraction of pesticide applied found on foil and vine respectively, averages estimated following discussions with the authors). Full vegetation (stage III) was given the 1:1 drift correction ratio because sprayers drift curves were established on that stage.

$$\text{Drift correction ratio} = \frac{F\text{air stage n}}{F\text{air stage III}} \qquad \text{Equation 1}$$

The values of $f_l$ (pesticide fraction deposited on leaves) and $f_s$ (pesticide fraction deposited on soil) are obtained through the following formula for non-covered soils:

$$f_l = F_{vine} \text{ and } f_s = F_{soil} \text{ for which } f_d + f_l + f_s = 1 \qquad \text{Equations 2, 3 and 4}$$

In the case of mixed cropping system, a complementary interception factor needs to be added for cover crop ($f_{l\text{covercrop}}$), resulting to the following equation:

$$f_d + f_s + f_{l(\text{vine})} + f_{l(\text{covercrop})} = 1. \qquad \text{Equation 5}$$

The structure of PestLCI 2.0 being fixed with 3 $f$ entries ($f_d$, $f_l$, and $f_s$), a combined $f_l$ has been calculated: ($f_{lc}$)

$$f_{lc} = F_{vine} + F_{covercrop} \qquad \text{Equation 6}$$

The fraction of deposited pesticide intercepted by the cover-crop is obtained as follows, the cover-crop being considered as a grass cover:

$$F_{covercrop} = F_{soil} * p_{covercrop} * f_{grass} \qquad \text{Equation 7}$$

with $F_{soil}$ = bare soil interception fraction of deposited pesticide in non-cover cropped vineyard,
$p_{covercrop}$ = percentage of inter-row surface covered by cover-crop
$f_{grass}$ = interception factor of grass

Table S4: Interception factors for mixed canopies (vine + cover-crop)

| Vine Stage | cover crop density | % of soil surface covered by grass | $F_{vine}$ | $f_{grass}$ | $F_{air}$ % spray lost in air *(calculation)* | % intercepted by cover crop *(calculation)* | $f_{lc}$ |
|---|---|---|---|---|---|---|---|
| **0** | none | 0 | 0,1 | 0 | 30% | 0% | 0,10 |
| **0** | weak (30%) | 30% | 0,1 | 0,3 | 30% | 5% | 0,15 |
| **0** | weak (30%) | 50% | 0,1 | 0,3 | 30% | 9% | 0,19 |
| **0** | weak (30%) | 80% | 0,1 | 0,3 | 30% | 14% | 0,24 |
| **0** | weak (30%) | 100% | 0,1 | 0,3 | 30% | 18% | 0,28 |
| **0** | high (70%) | 30% | 0,1 | 0,7 | 30% | 13% | 0,23 |
| **0** | high (70%) | 50% | 0,1 | 0,7 | 30% | 21% | 0,31 |
| **0** | high (70%) | 80% | 0,1 | 0,7 | 30% | 34% | 0,44 |
| **0** | high (70%) | 100% | 0,1 | 0,7 | 30% | 42% | 0,52 |
| **I** | average (50%) | 0 | 0,3 | 0,5 | 30% | 0% | 0,30 |
| **I** | average (50%) | 30% | 0,3 | 0,5 | 30% | 6% | 0,36 |
| **I** | weak (30%) | 50% | 0,3 | 0,3 | 30% | 6% | 0,36 |
| **I** | weak (30%) | 80% | 0,3 | 0,3 | 30% | 10% | 0,40 |
| **I** | weak (30%) | 100% | 0,3 | 0,3 | 30% | 12% | 0,42 |
| **I** | high (70%) | 50% | 0,3 | 0,7 | 30% | 14% | 0,44 |
| **I** | high (70%) | 80% | 0,3 | 0,7 | 30% | 22% | 0,52 |
| **I** | high (70%) | 100% | 0,3 | 0,7 | 30% | 28% | 0,58 |
| **II** | average (50%) | 0 | 0,5 | 0,5 | 30% | 0% | 0,50 |
| **II** | average (50%) | 30% | 0,5 | 0,5 | 30% | 3% | 0,53 |
| **II** | average (50%) | 50% | 0,5 | 0,5 | 30% | 5% | 0,55 |
| **II** | weak (30%) | 80% | 0,5 | 0,3 | 30% | 5% | 0,55 |
| **II** | weak (30%) | 100% | 0,5 | 0,3 | 30% | 6% | 0,56 |
| **II** | high (70%) | 80% | 0,5 | 0,7 | 30% | 11% | 0,61 |
| **II** | high (70%) | 100% | 0,5 | 0,7 | 30% | 14% | 0,64 |
| **III** | average (50%) | 0 | 0,65 | 0,5 | 25% | 0% | 0,65 |
| **III** | average (50%) | 30% | 0,65 | 0,5 | 25% | 2% | 0,67 |
| **III** | average (50%) | 50% | 0,65 | 0,5 | 25% | 3% | 0,68 |
| **III** | average (50%) | 80% | 0,65 | 0,5 | 25% | 4% | 0,69 |
| **III** | average (50%) | 100% | 0,65 | 0,5 | 25% | 5% | 0,70 |
| **IV** | average (50%) | 0 | 0,55 | 0,5 | 35% | 0% | 0,55 |
| **IV** | average (50%) | 30% | 0,55 | 0,5 | 35% | 2% | 0,57 |
| **IV** | average (50%) | 50% | 0,55 | 0,5 | 35% | 3% | 0,58 |
| **IV** | average (50%) | 80% | 0,55 | 0,5 | 35% | 4% | 0,59 |
| **IV** | average (50%) | 100% | 0,55 | 0,5 | 35% | 5% | 0,60 |

Table S5: Climatic profiles introduced in PestLCI 2.0 for Middle Loire Valley viticulture cases

| Location | Latitude | Longitude | Elevation (m) | annual datasets | average datasets | TMR covered |
|---|---|---|---|---|---|---|
| Beaucouzé | 47°28'42"N | 0°36'48"W | 50 | Oct.2009: sept.2012 | 3 years average months oct. (2009:2011) : sept. (2010:2012) and 2 sets of 30 years average months jan. 1971:dec. 2000 and jan. 1981:dec. 2010 | General |
| Fontaine-Guérin | 47°29'30"N | 0°10'00"W | 41 | Oct.2009: sept.2012 | 3 years average months oct.(2009:2011):sept.(2010:2012) | 3 |
| Martigné-Briand | 47°15'06"N | 0°26'06"W | 74 | Oct.2009: sept.2012 | 3 years average months oct.(2009:2011):sept.(2010:2012) | 2 and 5 |
| Beaulieu-S-Layon | 47°18'30"N | 0°35'48"W | 81 | Oct.2009: sept.2012 | 3 years average months oct.(2009:2011):sept.(2010:2012) | 4 |
| Blaison-Gohier | 47°23'42"N | 0°21'24"W | 68 | Oct.2009: sept.2012 | 3 years average months oct.(2009:2011):sept.(2010:2012) | 1 |

Table S6: Characteristics of soils introduced in PestLCI 2.0 for the study

| Name | Layer | Start depth | End depth | Clay content (<2µm) | Silt content (2-50µm) | Sand content (>50µm) | Organic carbon | pH of water | Bulk density |
|---|---|---|---|---|---|---|---|---|---|
| | | m | m | % | % | % | % | | 1000 kg/m3 |
| UTB 25 (altérite-calcaire lacustre) | 1 | 0 | 0.25 | 15 | 20 | 65 | 0 | 8.4 | 1.73 |
| | 2 | 0.25 | 0.5 | 15 | 40 | 5 | 0.63 | 8.5 | 1.67 |
| | 3 | 0.5 | 0.7 | 40 | 40 | 20 | 0.5 | 8.5 | 1.43 |
| | 4 | 0.7 | 1 | 25 | 40 | 35 | 0.2 | 8.5 | 1.39 |
| UTB 131 (roche-schiste greseux à grès) | 1 | 0 | 0.25 | 15 | 40 | 45 | 0.55 | 6.4 | 1.71 |
| | 2 | 0.25 | 0.5 | 15 | 40 | 45 | 0.95 | 6.2 | 1.71 |
| | 3 | 0.5 | 1 | | mother rock | | 0 | 6.2 | 2 |
| UTB 11 (sable éolien sur altération de schiste) | 1 | 0 | 0.2 | 10 | 35 | 55 | 0.38 | 6.6 | 1.75 |
| | 2 | 0.2 | 0.45 | 10 | 35 | 55 | 0.76 | 6.6 | 1.75 |
| | 3 | 0.45 | 0.6 | 15 | 40 | 45 | 0.2 | 6.6 | 1.75 |
| | 4 | 0.6 | 0.65 | 25 | 40 | 35 | 0.2 | 6.6 | 1.67 |
| | 5 | 0.65 | 0.8 | 25 | 40 | 35 | 0 | 6.6 | 1.67 |
| | 6 | 0.8 | 1 | | mother rock | | 0 | 6.6 | 2 |
| UTB 35 (recouvrement de formation sénoniennes sur formations carbonatées du crétacé supérieur) | 1 | 0 | 0.4 | 15 | 40 | 45 | 0.878 | 8.2 | 1.39 |
| | 2 | 0.4 | 0.65 | 15 | 40 | 45 | 0.581 | 8.3 | 1.43 |
| | 3 | 0.65 | 0.8 | 40 | 40 | 20 | 0.2 | 8.3 | 1.43 |
| | 4 | 0.8 | 1 | 15 | 40 | 45 | 0.2 | 8.3 | 1.39 |
| UTB 156 (roche-métagrauwacke parfois friable) | 1 | 0 | 0.3 | 25 | 40 | 35 | 1.59 | 6.0 | 1.73 |
| | 2 | 0.3 | 0.4 | 25 | 40 | 35 | 1.7 | 6.5 | 1.73 |
| | 3 | 0.4 | 1 | | mother rock | | 0 | 6.5 | 2 |

Numbers in green are estimates.

When mother rock was present, the same soil composition of the soil above the rock was assumed for the rock layer.

Table S7: Characteristics of the sprayers of which wind drift equations were introduced into PestLCI 2.0 for this study

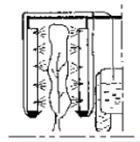
| Name of sprayer | image | type of sprayer | Diffusers type | position of the diffuser | nb of valid trials for drift curve defintion | source |
|---|---|---|---|---|---|---|
| recycling tunnel |  | air- or non air assisted sprayer where specific panels prevent drift and collect the spray mixture not applied on the leaves in order to re-use it | type of nozzles not specified | between the rows: each face of row treated by 5 levels of nozzles placed close to it in the interrow placed inside the tunnel | 21 | Ganzelmeier 2000 |
| VS10 |  | Canon "spider vault" 8 rows | canons | over the vine row, each row treated on one face by a canon | 15 | Codis etal 2011 |
| CG |  | pneumatic sprayer side by side | Berthoud air mist diffusers | over the vine row, each face of row treated by a diffuser placed over the row | 12 | Codis etal 2011 |
| ABMost |  | pneumatic sprayer side by side | Berthoud air mist diffusers | between the rows: each face of row treated by 2 diffusers placed close to it in the interrow | 13 | Codis etal 2011 |
| GRV Fantip |  | air-assisted sprayer side by side | Flat fan nozzles | between the rows: each face of row treated by 3 levels of nozzles placed close to it in the interrow | 2 | Codis etal 2011 |
| GRV IDK | idem, only nozzles change | air-assisted sprayer side by side | Air Induction Flat Spray Tips nozzles Lechler-IDK (drift | between the rows: each face of row treated by 3 levels of nozzles placed close to it in the interrow | 2 | Codis etal 2011 |
| GRV AVI air assisted | idem, only nozzles change | air-assisted sprayer side by side | Air Induction Flat Spray Tips nozzles Albuz-AVI | between the rows: each face of row treated by 3 levels of nozzles placed close to it in the interrow | 1 | Codis etal 2011 |
| GRV AVI non-air assisted | idem, only nozzles and air assitance change | non air-assisted sprayer side by side | Air Induction Flat Spray Tips nozzles Albuz-AVI | between the rows: each face of row treated by 3 levels of nozzles placed close to it in the interrow | 1 | Codis etal 2011 |
| Pendillard TVI |  | non air-assisted sprayer side by side | Air Induction Hollow Cone Spray Tip TVI (drift reducing | between the rows: each face of row treated by 3 levels of nozzles placed close to it in the interrow | 3 | Codis etal 2011 |

Table S8: Wind drift equations introduced into PestLCI 2.0 for this study.

| **Sprayer** | **Drift curve**[1] | **A** | **B** |
|---|---|---|---|
| Recycling tunnel | exponential | 0.038 | 0.057 |
| V10S: Canon Spider vault 8 rows | power | 68.9 | 1.02 |
| CG: pneumatic sprayer side by side | power | 7.5 | 0.75 |
| ABMOST: pneumatic sprayer side by side | power | 52.4 | 1.30 |
| GRV FanTip | power | 99.0 | 1.66 |
| GRV IDK | power | 3.51 | 0.84 |
| GRV AVI air assisted | power | 6.67 | 1.03 |
| GRV AVI non-air assisted | power | 2.04 | 0.67 |
| Pendillard TVI | exponential | 0.96 | 0.11 |

1: All equations take the form of a power function, $f(x) = A*x^{-B}$, except the Pendillard TVI and the recycling tunnel, where an exponential function ($f(x) = A*e^{-B}$) was found to give a better fit. In both equations, $f(x)$ is the fraction of pesticide emitted, and x the distance between the sprayer and the field border. The table shows the parameters A and B.

Table S9: Primary and secondary sources of data used for USETox$^{TM}$ CFs calculation

| **Parameter** | **Unit** | **Primary source** | **Secondary source** |
|---|---|---|---|
| **MW** | $g.mol^{-1}$ | PPDB | EPI Suite |
| **$K_{OW}$** | - | PPDB | EPI Suite: experimental > KOWWIN estimate from water solubility |
| **Koc** | $L.kg^{-1}$ | PPDB | EPI Suite: KOCWIN MCI method |
| **$K_H$25C** | $Pa.m^{3}.mol^{-1}$ | PPDB | EPI Suite: HenryWin Bond Estimate |
| **Pvap25** | Pa | PPDB | EPI Suite: Antoine estimate |
| **Sol25** | $mg.L^{-1}$ | PPDB | EPI Suite: WskowWin estimate |
| **$kdeg_A$** | $s^{-1}$ | EPI Suite: Based on Half-Life in air (t½), Level III Fugacity Model (k = ln(2)/t½) | |
| **$kdeg_W$** | $s^{-1}$ | EPI Suite: Based on Half-Life in water (t½), Level III Fugacity Model (k = ln(2)/t½) | |
| **$kdeg_{Sd}$** | $s^{-1}$ | EPI Suite: Based on Half-Life in sediment (t½), Level III Fugacity Model (k = ln(2)/t½) | |
| **$kdeg_{Sl}$** | $s^{-1}$ | PPDB | EPI Suite: Based on Half-Life in soil (t½), Level III Fugacity Model (k = ln(2)/t½) |
| **$av_{logEC50}$** | $mg.L^{-1}$ | ECOTOX database | EPI Suite |

Table S10: Input parameters for the calculation of CFs. Inputs for KDOC, KpSS, KpSd and kdegP are 0. The last two columns relate to the data behind the calculation of avlogEC50

| **Active substance** | **MW** g.mol$^{-1}$ | **KOW** - | **Koc** L.kg$^{-1}$ | **KH25C** Pa.m$^{3}$.mol$^{-1}$ | **Pvap25** Pa | **Sol25** mg.L$^{-1}$ | **kdegA** s$^{-1}$ | **kdegW** s$^{-1}$ | **kdegSd** s$^{-1}$ | **kdegSl** s$^{-1}$ | **avlogEC50** mg.L$^{-1}$ | **# of species** | **# of trophic levels** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ametoctradine | 275.39 | 25100 | 7713 | 4.13E-07 | 2.1E-10 | 0.15 | 2.96E-05 | 2.14E-07 | 2.38E-08 | 4.07E-07 | -1.08 | 3 | 3 |
| Benalaxyl-M | 325.4 | 4786.301 | 7175 | 0.000233 | 5.95E-05 | 33 | 2.05E-05 | 2.14E-07 | 2.38E-08 | 1E-07 | 0.79 | 3 | 3 |
| Benthiavalicarbe | 339.5 | 7.762471 | 1374 | 5.89E-12 | 3.06E-11 | 1247 | 3.44E-05 | 1.34E-07 | 1.49E-08 | 6.69E-08 | 1.30 | 0 | 0 |
| Boscalid (510) | 343.21 | 912.0108 | 9462 | 5.18E-08 | 7.2E-07 | 4.6 | 6.78E-06 | 1.34E-07 | 1.48E-08 | 6.8E-08 | 0.28 | 3 | 3 |
| Cyazofamid | 324.78 | 1584.893 | 516.5 | 0.0403 | 1.33E-05 | 0.114 | 3.06E-05 | 1.34E-07 | 1.48E-08 | 1.78E-06 | -1.16 | 3 | 3 |
| Flazasulfron | 407.37 | 0.871 | 46 | 2.58E-06 | 1.33E-05 | 2100 | 0.000151 | 4.46E-08 | 4.95E-09 | 8.02E-07 | -0.45 | 4 | 3 |
| Fluopicolide | 383.58 | 794 | 24810 | 4.15E-05 | 3.03E-07 | 2.8 | 3.57E-06 | 4.46E-08 | 4.95E-09 | 5.78E-08 | -1.11 | 3 | 3 |
| Folpet | 2.97E+02 | 1.05E+03 | 3.04E+02 | 8.00E-03 | 2.10E-05 | 8.0E-01 | 2.36E-05 | 4.01E-04 | 4.01E-04 | 2.67E-06 | -1.63E+00 | 26 | 4 |
| Mepanipyrim | 223.27 | 1910 | 1872 | 0.00167 | 2.32E-05 | 2.08 | 0.000147 | 2.14E-07 | 2.38E-08 | 1.41E-07 | -0.62 | 3 | 3 |
| Meptyldinocap | 364.39 | 3550000 | 61570 | 0.0116 | 7.92E-06 | 0.248 | 2.61E-05 | 2.14E-07 | 2.38E-08 | 5.35E-07 | -1.40 | 3 | 3 |
| Metrafenone | 409.3 | 19952.62 | 7061 | 0.132 | 0.000153 | 0.492 | 0.000153 | 1.34E-07 | 1.48E-08 | 5.49E-08 | -0.39 | 3 | 3 |
| Proquinazid Technique | 372.2 | 316000 | 300.2 | 0.03 | 0.00009 | 0.93 | 2.4E-05 | 2.14E-07 | 2.38E-08 | 2.63E-07 | -0.69 | 3 | 3 |
| Pyraclostrobine | 387.8 | 9772.372 | 9304 | 5.31E-06 | 2.6E-08 | 1.9 | 0.000155 | 1.34E-07 | 1.48E-08 | 2.51E-07 | -1.66 | 3 | 3 |
| Quinoxyfen | 308.13 | 45708.82 | 87370 | 0.0319 | 0.000012 | 0.047 | 4.01E-06 | 4.46E-08 | 4.95E-09 | 8.27E-08 | -0.89 | 6 | 3 |
| Spinosad (spinosyn A) | 731.95 | 1995.262 | 28180 | 8.46E-19 | 5.45E-17 | 0.3318 | 0.000513 | 4.46E-08 | 4.95E-09 | 2.23E-08 | -0.29 | 2 | 2 |
| Spiroxamine | 297.5 | 776.2471 | 2347 | 0.0038 | 0.0035 | 405 | 9.63E-05 | 1.34E-07 | 1.48E-08 | 3.21E-07 | -0.54 | 5 | 3 |
| Tetraconazole | 372.15 | 3630 | 14120 | 0.00036 | 0.00018 | 156.6 | 8.23E-06 | 4.46E-08 | 4.95E-09 | 1.87E-08 | 0.40 | 5 | 3 |
| Trifloxystrobine | 408.37 | 31600 | 3040000 | 0.0023 | 3.4E-06 | 0.61 | 5.28E-06 | 1.34E-07 | 1.49E-08 | 1.15E-06 | -1.84 | 5 | 3 |
| Zoxamide | 336.64 | 5754.399 | 1224 | 0.00659 | 0.000013 | 0.681 | 8.06E-06 | 4.46E-08 | 4.95E-09 | 1.34E-06 | -1.26 | 3 | 3 |

Table S11: USETox$^{TM}$ CFs calculated for the viticulture study and reason for flagging 6 CFs interim according to the USETox$^{TM}$ classification (U: urban, C : continental)

| | CFs | | | | | | Interim? | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Active substance** | **Em.air U** | **Em.air C** | **Em.fr.water C** | **Em.sea waterC** | **Em.nat.soil C** | **Em.agr. soilC** | **Dissociating** | **Inorganic** | **Surfactant** | **Organo-metallic** | **Ecotox EF** | **Overall** |
| Ametoctradine | 6.6E+02 | 4.1E+02 | 1.7E+04 | 5.2E-06 | 1.2E+01 | 1.2E+01 | X | | | | | X |
| Benalaxyl-M | 6.4E+01 | 2.7E+01 | 2.8E+03 | 1.9E-04 | 8.6E+00 | 8.6E+00 | | | | | | |
| Benthiavalicarbe | 1.4E+03 | 1.1E+03 | 2.6E+04 | 2.7E-10 | 5.8E+02 | 5.8E+02 | X | | | | X | X |
| Boscalid (510) | 5.0E+02 | 3.2E+02 | 1.2E+04 | 7.2E-07 | 4.1E+01 | 4.1E+01 | | | | | | |
| Cyazofamid | 5.5E+03 | 1.6E+03 | 3.7E+05 | 2.9E+00 | 8.4E+02 | 8.4E+02 | | | | | | |
| Flazasulfron | 2.5E+03 | 8.1E+02 | 1.3E+05 | 2.0E-04 | 5.9E+03 | 5.9E+03 | X | | | | | X |
| Fluopicolide | 1.4E+04 | 8.4E+03 | 3.7E+05 | 3.3E-02 | 6.1E+02 | 6.1E+02 | | | | | | |
| Folpet | 1.2E+01 | 4.8E+00 | 6.1E+02 | 6.9E-07 | 1.6E+00 | 1.6E+00 | | | | | | |
| Mepanipyrim | 1.4E+03 | 2.4E+02 | 7.9E+04 | 1.4E-02 | 6.4E+02 | 6.4E+02 | X | | | | | X |
| Meptyldinocap | 2.7E+03 | 9.9E+02 | 1.4E+05 | 2.5E-01 | 1.1E+01 | 1.1E+01 | | | | | | |
| Metrafenone | 3.1E+02 | 3.7E+01 | 5.1E+04 | 1.9E-01 | 2.8E+02 | 2.8E+02 | | | | | | |
| Proquinazid Technique | 1.5E+03 | 6.7E+02 | 8.2E+04 | 5.5E-01 | 2.0E+03 | 2.0E+03 | | | | | | |
| Pyraclostrobine | 1.8E+04 | 4.5E+03 | 1.0E+06 | 9.8E-04 | 9.9E+02 | 9.9E+02 | | | | | | |
| Quinoxyfen | 3.7E+03 | 2.1E+03 | 1.1E+05 | 6.5E+00 | 4.7E+01 | 4.7E+01 | | | | | | |
| Spinosad (spinosyn A) | 2.2E+03 | 1.4E+03 | 5.4E+04 | 9.4E-17 | 2.1E+02 | 2.1E+02 | | | | | X | X |
| Spiroxamine | 1.5E+03 | 2.7E+02 | 8.9E+04 | 4.7E-02 | 2.5E+02 | 2.5E+02 | | | | | | |
| Tetraconazole | 4.5E+02 | 2.6E+02 | 1.4E+04 | 9.1E-03 | 1.2E+02 | 1.2E+02 | X | | | | | X |
| Trifloxystrobine | 9.8E+02 | 5.6E+02 | 3.0E+04 | 1.6E-02 | 2.7E-01 | 2.7E-01 | | | | | | |
| Zoxamide | 2.3E+04 | 1.3E+04 | 8.0E+05 | 8.4E+00 | 1.0E+03 | 1.0E+03 | | | | | | |

Table S12: Characteristics of PAIs applications for 2011 on TMRs 1, 2 and 3. *In grey: the inorganic and partially inorganic PAIs that were not included in this study.*

| | **PAIs** | **Application rate (kg/ha)** | **Crop type + development stage** | **Month of application** | **Application method** | **width treated at a time** |
|---|---|---|---|---|---|---|
| TMR1 | Amitrole | 0.79 | Grass I - all phases | April | sheltered boom | 1.85 |
| | Aclonifen | 0.31 | Grass I - all phases | April | sheltered boom | 1.85 |
| | Sulfur | 5.89 | *Vines II - h80% grass | May | tunnel sprayer | 1.85 |
| | Folpet | 0.74 | *Vines II - h80% grass | May | tunnel sprayer | 1.85 |
| | Fosetyl-Aluminium | 1.47 | *Vines II - h80% grass | May | tunnel sprayer | 1.85 |
| | Fluopicolide | 0.12 | *Vines II - h80% grass | May | airblast sprayer | 7.4 |
| | Fosetyl-Aluminium | 1.75 | *Vines II - h80% grass | May | airblast sprayer | 7.4 |
| | Proquinazid Technique | 0.05 | *Vines II - h80% grass | May | airblast sprayer | 7.4 |
| | Tétraconazole | 0.03 | *Vines III - a80% grass | June | airblast sprayer | 7.4 |
| | Indoxacarbe | 0.04 | *Vines III - a80% grass | June | airblast sprayer | 7.4 |
| | copper oxychloride | 0.73 | *Vines III - a80% grass | July | airblast sprayer | 7.4 |
| | copper sulfate | 0.18 | *Vines III - a80% grass | July | airblast sprayer | 7.4 |
| | Cymoxanil | 0.12 | *Vines III - a80% grass | July | airblast sprayer | 7.4 |
| | Mancozèbe | 0.40 | *Vines III - a80% grass | July | airblast sprayer | 7.4 |
| TMR 2 | Amitrole | 1,603 | Grass I - all phases | April | sheltered boom | 2 |
| | Ammonium thiocyanate | 1,505 | Grass I - all phases | April | sheltered boom | 2 |
| | Glyphosate | 0,9 | Grass I - all phases | April | sheltered boom | 2 |
| | Sulfur | 6,4 | *Vines I - a30% grass | April | pneumatic sprayer side by side | 6 |
| | Méfénoxam | 0,072 | *Vines II - a30% grass | May | pneumatic sprayer side by side | 6 |
| | Mancozeb | 1,15 | *Vines II - a30% grass | May | pneumatic sprayer side by side | 6 |
| | Metrafenone | 0,08474 | *Vines II - a30% grass | May | pneumatic sprayer side by side | 6 |
| | Sulfur | 8 | *Vines II - a30% grass | May | pneumatic sprayer side by side | 6 |
| | Disodium phosphonate | 0,75 | *Vines III - a30% grass | June | pneumatic sprayer side by side | 6 |
| | Cyazofamid | 0,08 | *Vines III - a30% grass | June | pneumatic sprayer side by side | 6 |
| | Fenbuconazole | 0,0375 | *Vines III - a30% grass | June | pneumatic sprayer side by side | 6 |
| | Metrafenone | 0,8474 | *Vines III - a30% grass | June | pneumatic sprayer side by side | 6 |
| | Indoxacarbe | 0,038 | *Vines III - a30% grass | June | pneumatic sprayer side by side | 6 |
| | Fenbuconazole | 0,0375 | *Vines III - a30% grass | July | pneumatic sprayer side by side | 6 |
| TMR3 | Glyphosate | 0.54 | Grass I - all phases | March | sheltered boom | 1.95 |
| | Amitrole | 0.92 | Grass I - all phases | March | sheltered boom | 1.95 |
| | ammonium thiocyanate | 0.86 | Grass I - all phases | March | sheltered boom | 1.95 |
| | Flazasulfuron | 0.02 | Grass I - all phases | March | sheltered boom | 1.95 |
| | Glyphosate | 0.09 | Grass I - all phases | May | sheltered boom | 1.95 |
| | Trifloxystrobin | 0.06 | *Vines II - a50% grass | May | pneumatic sprayer side by side | 7.8 |
| | Trifloxystrobin | 0.06 | *Vines III - a50% grass | June | pneumatic sprayer side by side | 7.8 |
| | Diméthomorph | 0.18 | *Vines III - a50% grass | June | pneumatic sprayer side by side | 7.8 |
| | Mancozèbe | 1.20 | *Vines III - a50% grass | June | pneumatic sprayer side by side | 7.8 |
| | Difénoconazole | 0.03 | *Vines III - a50% grass | July | pneumatic sprayer side by side | 7.8 |
| | Meptyldinocap | 0.21 | *Vines III - a50% grass | July | pneumatic sprayer side by side | 7.8 |

Table S13: Overview of parameters assessed in sensitivity analysis of PestLCI 2.0 input parameters, and their sensitivities

| **Parameter** | | **Sensitivity** | |
|---|---|---|---|
| | **f(air)** | **f(sw/ag.soil)** | **f(gw)** |
| Interception fraction | 9.85E-01 | -6.94E+00 | -6.94E+00 |
| Field width | -8.19E-04 | 6.05E-05 | 6.05E-05 |
| Field length | 0 | 0 | 0 |
| Slope | <1.00E-10 | 1.27E+00 | -1.31E-03 |
| Soil material density (kg/l) | <1.00E-10 | <1.00E-10 | <1.00E-10 |
| Fraction macropores | <1.00E-10 | <1.00E-10 | 3.94E-01 |
| Soil solid matter fraction | 1.95E-04 | -8.30E-01 | 3.25E+00 |
| Soil water fraction | 2.05E-03 | -7.53E-01 | 2.14E+00 |
| Reference soil moisture content | 4.91E-04 | 7.56E-01 | 7.56E-01 |
| Response factor biodegr rate | <1.00E-10 | <1.00E-10 | <1.00E-10 |
| Q-value | -5.18E-05 | -7.84E-02 | -7.84E-02 |
| Air boundary layer (m) | -1.16E-03 | 1.07E-03 | 1.07E-03 |
| Nozzle distance (m) | -9.69E-07 | 7.16E-08 | 7.16E-08 |
| Molecular weight (g/mol) | 1.17E-03 | -1.07E-03 | -1.07E-03 |
| Molecular volume (cm3/mol) | 8.33E-02 | 6.82E-04 | 6.82E-04 |
| Solubility (g/l) | -1.16E-03 | 1.07E-03 | 1.07E-03 |
| Vapour pressure (Pa) | 4.25E-01 | -1.12E-03 | -1.12E-03 |
| log K(ow) | <1.00E-10 | <1.00E-10 | <1.00E-10 |
| K(oc) (l/kg) | -2.67E-03 | -5.87E-01 | -8.44E-01 |
| Soil t(1/2) (days) | 6.98E-04 | 1.08E+00 | 1.08E+00 |
| Atmospheric OH rate (cm3/molecules*sec) | -8.02E-01 | -2.22E-07 | -2.22E-07 |
| Elevation (m) | <1.00E+10 | <1.00E+10 | <1.00E+10 |
| T(average/chosen month)(degC) | 2.22E+00 | -7.00E-02 | -7.00E-02 |
| T(min/chosen month)(degC) | <1.00E-10 | <1.00E-10 | <1.00E-10 |
| T(max/chosen month)(degC) | <1.00E-10 | <1.00E-10 | <1.00E-10 |
| Rainfall(chosen month)(mm) | <1.00E-10 | <1.00E-10 | <1.00E-10 |
| Rain days(>1mm/chosen month)(-) | <1.00E-10 | <1.00E-10 | <1.00E-10 |
| Annual pot. evaporation (mm) | <1.00E-10 | <1.00E-10 | <1.00E-10 |
| Solar irradiation(chosen month)(Wh m-2 day | -2.97E+00 | -2.66E-07 | -2.66E-07 |
| f(OC) in topsoil | -2.67E-03 | -5.87E-01 | -8.44E-01 |
| f(OC) in all soil layers | -2.67E-03 | -5.87E-01 | -8.44E-01 |
| f(sand) | <1.00E-10 | <1.00E-10 | -7.29E-03 |
| f(silt) | <1.00E-10 | <1.00E-10 | 3.41E-03 |
| f(clay) | <1.00E-10 | <1.00E-10 | 2.31E-03 |
| pH of topsoil | <1.00E-10 | <1.00E-10 | <1.00E-10 |
| pH of all soil layers | <1.00E-10 | <1.00E-10 | <1.00E-10 |
| Soil bulk density | -2.67E-03 | 2.46E-03 | -8.45E-01 |

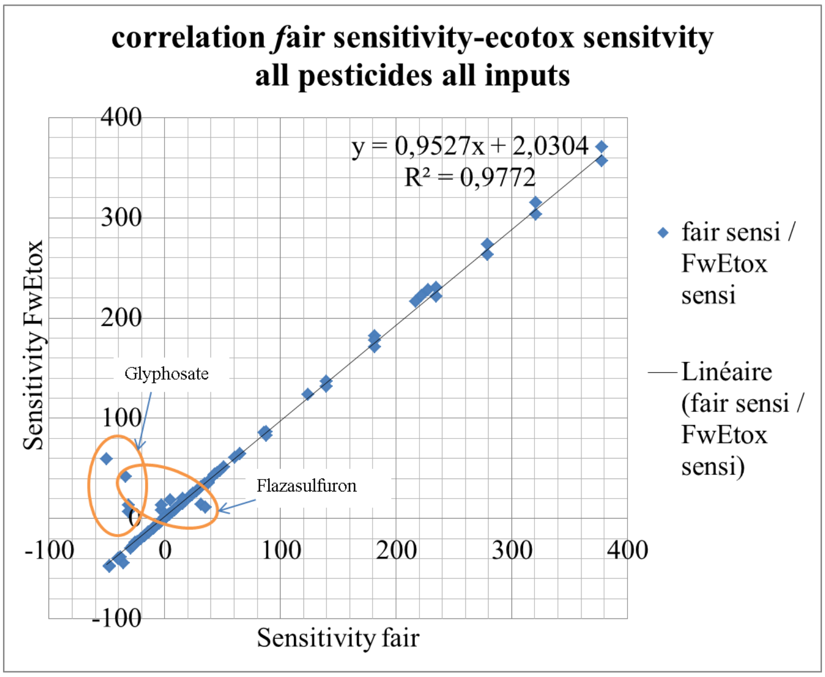


Fig. S1, correlation between sensitivity of f air and of FwEtox based on all tested inputs in scenario sensitivity analysis.

This correlation was verified for situations with the presence of a waterbody is considered (at 20m), air emissions remain dominant is such cases.

### S-E) scenario sensitivity analysis on 4 climatic datasets on a complete treatment program

For a same treatment program (TMR3 2010-2011), results obtained with the 4 climatic datasets are compared to results obtained with Fontaine Guérin 2010-2011in fig. S2. The fraction emitted to air ($f_{air}$) varies within a range of -50% to +65% when considering single PAIs applications, results vary within a much smaller range (-10%: +5%) for the full program average $f_{air}$. The results based on 30 years average climate data are close to the reference year results and the 3 more recent years average even closer. The fraction emitted to groundwater varies in much higher proportions but based on much lower emission fractions for $f_{gw}$ than for $f_{air}$.

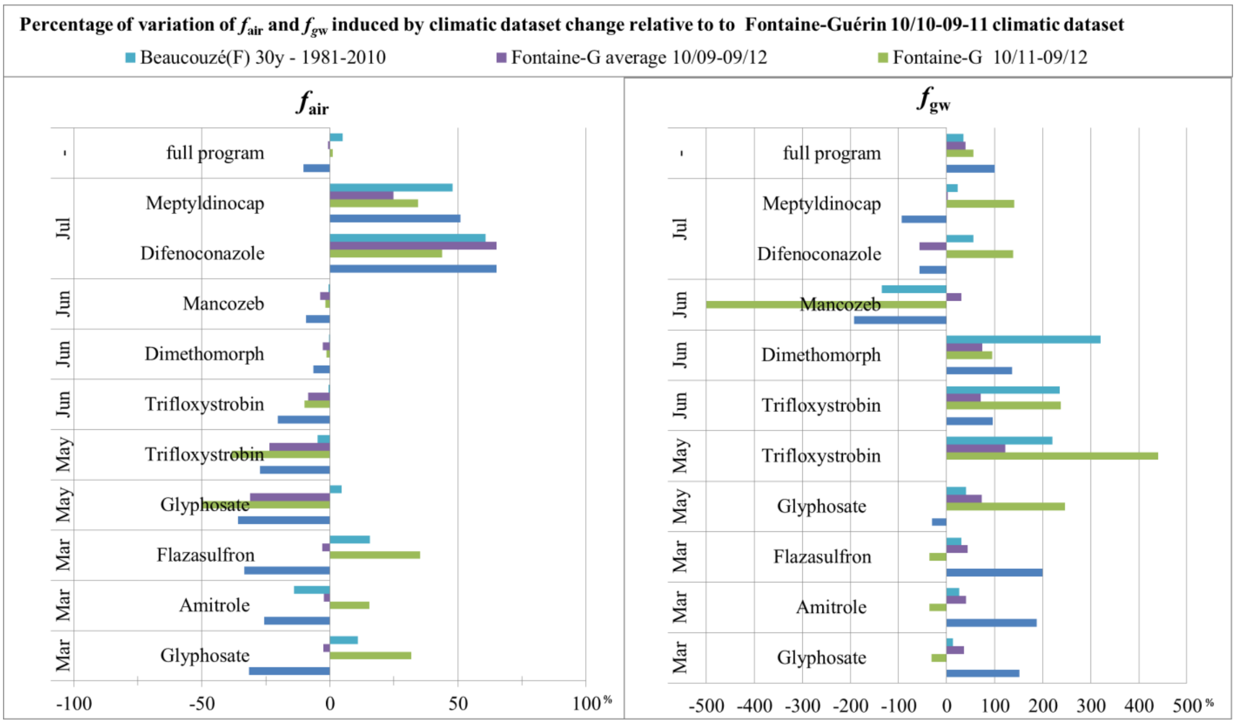


Fig. S2 Sensitivity of PAIs emissions to air ($f_{air}$) and groundwater ($f_{gw}$) to climatic dataset change (the bar (green) has been cut to -500 for Mancozeb in $f_{gw}$ chart, the value (-107415) is an artefact due to very small values of emissions).

# SYNTHESE

Ce deuxième chapitre visait à adapter le modèle d'émissions de pesticides PestLCI 2.0, conçu pour les grandes cultures, aux spécificités de la viticulture, afin de pouvoir intégrer les flux de substances actives aux calculs d'ACV.

Quatre modifications principales ont été apportées :

- le modèle d'émissions PestLCI 2.0 prend en compte le comportement des substances actives à travers leurs caractéristiques physico-chimiques. **Nous avons pu intégrer dans le modèle 29 nouvelles substances actives appliqués en viticulture** (le modèle en comptait antérieurement 90 pour toutes les cultures) ;

- le type de pulvérisateur influe fortement sur la dérive de la bouillie appliquée, Pest LCI2.0 est conçu pour prendre en compte les courbes de dérive des pulvérisateurs. **9 modèles de pulvérisateurs viticoles** ont donc été **intégrés** dans PestLCI 2.0 ;

- l'interception des pesticides par le feuillage détermine la quantité de substance susceptible de se volatiliser depuis les feuilles. **La prise en compte de la présence d'un couvert herbacé sur le sol du vignoble, a pu être ajoutée** dans PestLCI 2.0 aboutissant à des coefficients d'interception tenant compte à la fois de la densité du couvert herbacé, de son étendue et du développement de la surface foliaire de la vigne.

- Enfin, nous avons intégré des jeux de données météorologiques et de sol spécifiques aux parcelles de notre étude.

Par ailleurs, le calcul des facteurs de caractérisation de 18 substances actives pour le modèle de caractérisation USEtox$^{TM}$ a permis le calcul de l'impact écotoxicité aquatique d'eau douce.

**Grâce aux adaptations effectuées sur le modèle PestLCI 2.0, les spécificités de la viticulture à couvert végétal vertical sont prises en compte.** L'étude de sensibilité réalisée, nous a permis d'identifier le sol, le climat, et le type de pulvérisateur comme les facteurs les plus influents qui seront donc à privilégier lors des futurs inventaires de cycle de vie ou qui constitueront des points de vigilance lors de toute démarche d'évaluation des impacts.

**Le modèle ne peut toutefois pas prendre en charge les calculs concernant les matières actives inorganiques** telles le cuivre et le soufre, ce qui le rend **inopérant pour les cas de viticulture biologique**, et qui limite la portée des résultats pour les ITKv conventionnels qui font appel à des substances inorganiques. Par ailleurs les métabolites secondaires émis suite à la dégradation des pesticides ne sont pas pris en compte.

Les trois ITKv conventionnels ont fait l'objet de calcul des émissions et du potentiel d'écotoxicité aquatique en eau douce (FwEtoxP). L'ITKv correspondant au groupe 1 « traitements systématiques et travail manuel limité » a montré le plus fort impact FwEtoxP, principalement à cause de l'utilisation d'Aclonifen.

# TRANSITION

Le chapitre suivant présente le cadre méthodologique mis en œuvre pour l’ACV des cinq ITKv sélectionnés suite aux travaux présentés dans le chapitre 1. Il intègre les calculs d’émissions des pesticides et d’écotoxicité aquatique d’eau douce réalisés dans le chapitre 2. Il vise à observer dans quelle mesure l’ACV peut être adaptée et appropriée au choix des techniques viticoles à l’échelle parcellaire.

# CHAPITRE 4

# ECO-EFFICIENCY OF VINEYARD TECHNICAL MANAGEMENT ROUTES PART I: LIFE CYCLE ASSESSMENT DIFFERENTIATES CONTRASTED MANAGEMENT ROUTES AND TECHNIQUES

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## KEYWORDS:

Grape, viticulture, environment, LCA, practices, plot scale

## 1 INTRODUCTION

Since the past decade, winegrowers are increasingly committed to improving the environmental sustainability of their vineyards (Szolnoki 2013). Grape production has been shown to represent more than 50% of wine environmental impacts (Point et al. 2012; Neto et al. 2012; Gazulla et al. 2010). Sustainability programs mainly based on recommended good practices are found in many vineyards of the world (Belis-Bergouignan and Cazals 2006; Santiago-Brown et al. 2014; Corbo et al. 2014) and the organic vineyard area is rapidly increasing worldwide (Agence-Bio 2013). However a quantification of environmental impacts of their practices and technical management routes (TMRs) – the logical successions of technical options (TOs) designed by farmers (Sébillotte 1974) – would help winegrowers to make better technical choices and to identify improvement priorities. A better knowledge of the main environmental burdens of viticulture and of the contributions of technical operations to these burdens would also help to improve sustainability programs, organic production rules and their application, as well as Protected Denomination of Origin (PDO) specifications (European-Commission 2014). In parallel, viticulture extension officers and cooperative technicians, by a wide and clear view of the environmental impacts of the practices at field scale could more efficiently accompany the winegrowers in their technical choices (Sebillotte 1997). Field scale is particularly important in viticulture because vineyard TMRs are adjusted to each single plot due to a high variability between the plots in an estate in soil types, grape cultivars behavior and needs, and targeted wines.

This is why a transparent, reliable and accepted environmental impact assessment method is needed to identify the environmental burdens of vineyard management practices, and to help PDO winegrowers’ practices improvement at field scale.

Among the existing environmental assessment methods applied to agriculture, Life cycle assessment (LCA) is the one allowing today the most exhaustive appraisal (Bockstaller et al. 2009; Payraudeau and Vanderwerf 2005). It is a method standardized under ISO guidelines (ISO 2006). It calculates the eco-efficiency of a product, for different environmental impact categories, relating the environmental burdens to the product’s main function expressed by a common functional unit (FU) e.g. global warming potential for 1 bottle of wine. LCA takes into account all material fluxes and processes involved in the product elaboration, use and end of life (cradle to grave assessment). Therefore it permits to point out the main environmental burdens and their key drivers, and compare production systems (Nemecek et al. 2001; Alaphilippe et al. 2013).

LCA is currently applied and adapted to agricultural and food production systems (Audsley et al. 2003; Brentrup et al. 2004; van der Werf et al. 2013) and important databases of agricultural products and processes life cycle inventories are now available to support environmental impact studies (Eady et al. 2013b; Nemecek and Kägi 2007) or eco-labelling (Koch and Salou 2014).

Perennial fruit -of which wine and grape- LCA-based studies were published mostly in the past decade (Cerutti et al. 2014; Bessou et al. 2013; Benedetto et al. 2013). After critical reviews of most of them, for orchard fruits including grapes (Cerutti et al. 2011), for all perennials (Bessou et al. 2012, 2013), and for wine and grape (Benedetto et al. 2013), specific methodological recommendations can be formulated for LCAs of perennials in order to avoid the oversimplification frequently met in their assessment: i) the studies should consider the whole lifetime of the crop, culture installation (plantation, trellis building, non-productive years…), plants production (nursery) and yield decrease at the end of lifetime; ii) field emissions of N and P compounds, heavy metals and pesticide active ingredients (PAI.s) should be quantified as much as possible "crop-specifically" and the chosen methods should be well documented, iii) the complexity of interactions and relationships between the technical and natural spheres should be addressed and discussed including carbon sequestration; iv) the variability of yield and practices between years should be discussed and v) complementary FUs should be used relatively to the study objectives (surface, mass, quality). The recent development of LCA calculation tools dedicated to specific productions such as sugarcane (Renouf et al. 2013) or greenhouse crops (Torrellas et al. 2013) and designed to help farmers and their advisors in choosing techniques shows that the method may be relevant for decision aid.

Nevertheless, even when the results are presented in a regional perspective, specific processes to ensure the representativeness of the cases chosen, as done for example by Pradeleix et al. (2012) or Renaud-Gentié et al. (to be submitted), are rarely implemented. Moreover, as Bessou et al. (2013) points out in her review of LCA studies of perennial crops, the representativeness and variability of the results are barely discussed (Neto et al. 2012; Vázquez-Rowe et al. 2012b) or totally missing.

Additionally, only few authors have analyzed viticultural practices in detail (Neto et al. 2012; Point et al. 2012; Vázquez-Rowe et al. 2012b; Villanueva-Rey et al. 2014a; Fusi et al. 2014a), despite a contribution of the farm stage of up to 50% (Neto et al. 2012) to wine environmental impacts (Gazulla et al. 2010; Aranda et al. 2005; Neto et al. 2012; Bellon-Maurel et al. 2014). And, to our knowledge, no detailed assessment and comparison of vineyard practices was made to date, nor consideration of quality target of grape production was taken.

The concept of eco-efficiency was defined by WBCSD (World Business Council for Sustainable Development) in 2000 as “creating more value with less environmental impact” (WBCSD 2000), it can been expressed by dividing the environmental impact by the value of the product in order to obtain environmental impact per unit of production value (Huppes and Ishikawa 2005). We based our definition on this approach, considering the main different values or functions of grape production activity; however, we didn’t monetize these functions.

The general goal of our research is the assessment of grape production practices accounting simultaneously for environmental impact and grape quality. It is developed in two connected papers.

The aim of this first paper is to define and apply a LCA methodological framework to analyze the eco-efficiency of viticulture TMRs, in order to i) check its relevance for choosing TMRs or practices at a field scale, ii) analyse the structure of environmental impacts of the diversity of vineyard management of a wine production area.

In order to achieve this double goal, the following four objectives were pursued: i) define LCA processes and details with respect to crop and site specificities; ii) use LCA to determine the main environmental burdens of 5 TMRs representing the diversity of regional vineyard management, and the variability among the TMRs, iii) analyze the main drivers of eco-efficiency within single or combined technical operations and external environmental factors and iv) explore the relevance of the method for field scale techniques and TMR choice.

The second related paper proposes the inclusion of grape quality in eco-efficiency calculation.

# 2 MATERIAL AND METHODS

## 2.1 GENERAL FRAMEWORK

The overall structure of the research presented in the two papers is reported in Figure 21, part I (this paper) with solid lines and part II (second paper) with dotted lines.

The first step of the whole process, surveying regional diversity of the vineyard TMRs and establishing a typology based on TMR similarities and practices association through the Typ-iti method, is described in (Renaud-Gentié et al. to be submitted). A representative plot was chosen for each of the main types of TMRs given by the Typ-iti method. Then, concerning environmental assessment, data were collected: i) characteristics and quantities of inputs and operations conducted on the plot, the TMR represented as a chain (of practices) is the center of the assessment process, with soil and climatic conditions of the vineyard and cover-crop characteristics ii) quantities of inputs, operations conducted on the plot and model-based calculations of direct emissions support life cycle inventory for environmental impact calculations, iii). Eco-efficiency is then calculated and expressed per ha and per kg of grapes and the percentages of contribution of the TMR parts to each impact are analyzed. The value of LCA for TMR choice and design at field scale is evaluated at this stage.

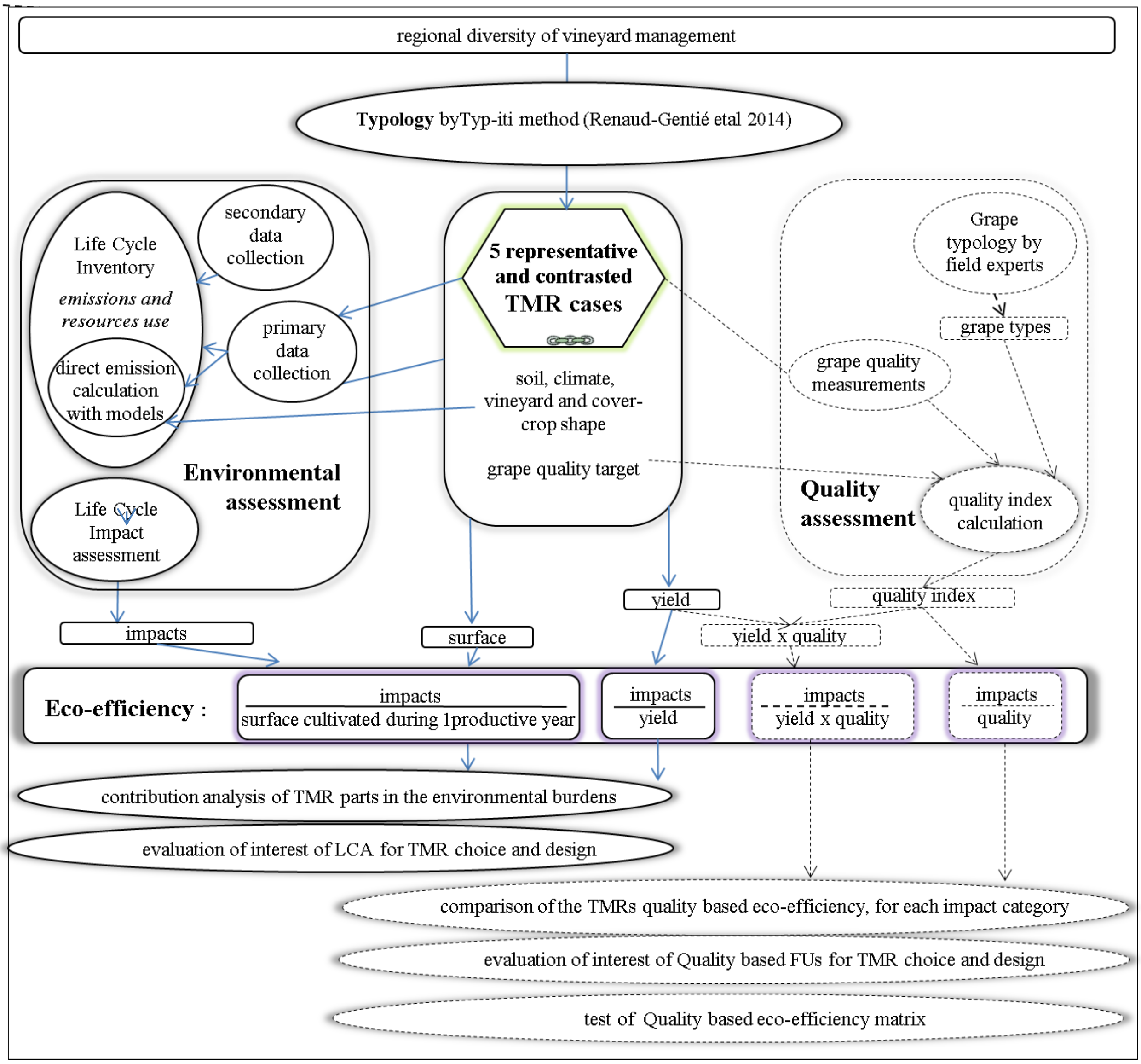
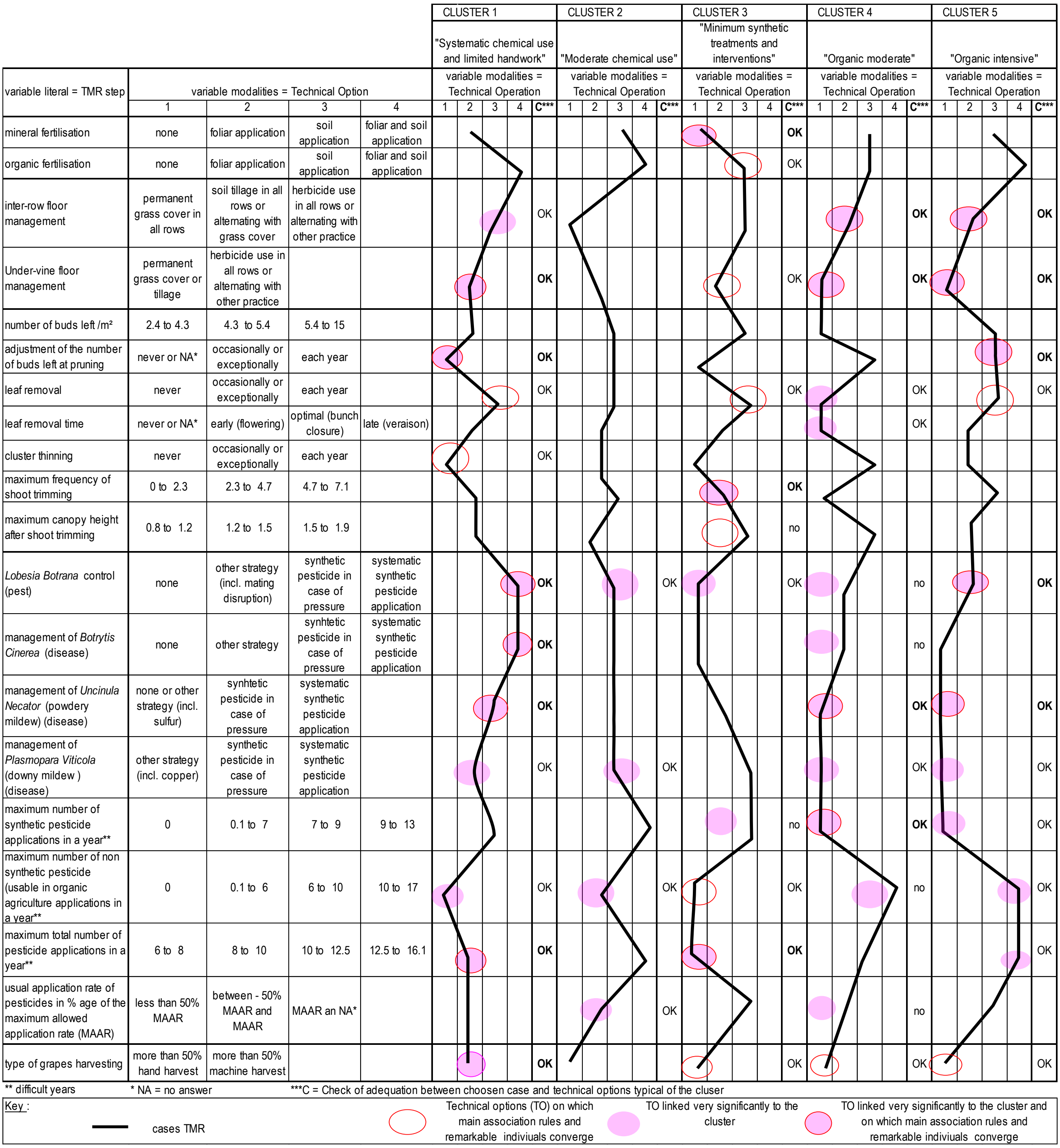


*Figure 21: General framework of the study “Eco-efficiency for vineyard TMR choice and design”. Part I, environmental assessment (paper 1) in solid lines and arrows and part II, inclusion of quality in the eco-efficiency assessment (paper 2) in dotted lines*

## 2.2 CHOICE OF REPRESENTATIVE TMRS

A typology of vineyard management of Chenin Blanc grapes grown for PDO dry white wine production in Middle Loire Valley was established on the basis of a survey of a sample of 77 TMRs of winegrowers (Renaud-Gentié et al. 2014). Five types of vineyard TMRs resulted from the analysis of this diversity: type 1 “systematic synthetic chemical use and limited handwork”, type 2 “moderate chemical use”, type 3 “minimum synthetic treatments and interventions”, type 4 “moderate organic” (i.e. with limited interventions), type 5 “intensive organic” (i.e. with many interventions). Typical characteristics of the clusters were derived by the Typ-iti method (Renaud-Gentié et al. 2014) which combines clustering based on multidimensional analysis and association rules. In Figure 22 these typical characteristics are materialized by three types of ovals, according to the analysis results which converged to identify each operation typical of each cluster (remarkable individuals: paragons and specifics, main association rules). Five plots from commercial vineyards of the area were chosen to represent the five types, and used for inventory and LCA calculations. These contrasted TMRs were selected to present as many as possible typical characteristics of the cluster they represent. The five real case TMRs are represented in Figure 22 by a bold black line stopping at the chosen TO at each TMR step.



| variable literal = TMR step | variable modalities = Technical Option | | | | CLUSTER 1 "Systematic chemical use and limited handwork" | CLUSTER 2 "Moderate chemical use" | CLUSTER 3 "Minimum synthetic treatments and interventions" | CLUSTER 4 "Organic moderate" | CLUSTER 5 "Organic intensive" |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | C*** | C*** | C*** | C*** | C*** |
| mineral fertilisation | none | foliar application | soil application | foliar and soil application | | | **OK** | | |
| organic fertilisation | none | foliar application | soil application | foliar and soil application | | | OK | | |
| inter-row floor management | permanent grass cover in all rows | soil tillage in all rows or alternating with grass cover | herbicide use in all rows or alternating with other practice | | OK | | | **OK** | **OK** |
| Under-vine floor management | permanent grass cover or tillage | herbicide use in all rows or alternating with other practice | | | **OK** | | OK | **OK** | **OK** |
| number of buds left /m² | 2.4 to 4.3 | 4.3 to 5.4 | 5.4 to 15 | | | | | | |
| adjustment of the number of buds left at pruning | never or NA* | occasionally or exceptionally | each year | | **OK** | | | | **OK** |
| leaf removal | never | occasionally or exceptionally | each year | | OK | | OK | OK | OK |
| leaf removal time | never or NA* | early (flowering) | optimal (bunch closure) | late (veraison) | | | | OK | |
| cluster thinning | never | occasionally or exceptionally | each year | | OK | | | | |
| maximum frequency of shoot trimming | 0 to 2.3 | 2.3 to 4.7 | 4.7 to 7.1 | | | | **OK** | | |
| maximum canopy height after shoot trimming | 0.8 to 1.2 | 1.2 to 1.5 | 1.5 to 1.9 | | | | no | | |
| *Lobesia Botrana* control (pest) | none | other strategy (incl. mating disruption) | synthetic pesticide in case of pressure | systematic synthetic pesticide application | **OK** | OK | OK | no | **OK** |
| management of *Botrytis Cinerea* (disease) | none | other strategy | synhetic pesticide in case of pressure | systematic synthetic pesticide application | **OK** | | | no | |
| management of *Uncinula Necator* (powdery mildew) (disease) | none or other strategy (incl. sulfur) | synhetic pesticide in case of pressure | systematic synthetic pesticide application | | **OK** | | | **OK** | **OK** |
| management of *Plasmopara Viticola* (downy mildew ) (disease) | other strategy (incl. copper) | synthetic pesticide in case of pressure | systematic synthetic pesticide application | | OK | OK | | OK | OK |
| maximum number of synthetic pesticide applications in a year** | 0 | 0.1 to 7 | 7 to 9 | 9 to 13 | | | no | **OK** | OK |
| maximum number of non synthetic pesticide (usable in organic agriculture applications in a year** | 0 | 0.1 to 6 | 6 to 10 | 10 to 17 | OK | OK | OK | no | OK |
| maximum total number of pesticide applications in a year** | 6 to 8 | 8 to 10 | 10 to 12.5 | 12.5 to 16.1 | **OK** | | **OK** | | OK |
| usual application rate of pesticides in % age of the maximum allowed application rate (MAAR) | less than 50% MAAR | between - 50% MAAR and MAAR | MAAR an NA* | | | OK | | no | |
| type of grapes harvesting | more than 50% hand harvest | more than 50% machine harvest | | | **OK** | | OK | OK | OK |

** difficult years

* NA = no answer

***C = Check of adequation between choosen case and technical options typical of the cluser

Key :

cases TMR

Technical options (TO) on which main association rules and remarkable indiviuals converge

TO linked very significantly to the cluster

TO linked very significantly to the cluster and on which main association rules and remarkable indiviuals converge

*Figure 22: Technical management routes of chosen cases in comparison to main characteristics of the cluster they represent*

For each TMR, the C column shows the checking of the convergence between the cases and the typical characteristics of the cluster.

## 2.3 ENVIRONMENTAL ASSESSMENT BY LCA

According to (ISO 2006), "LCA assesses, in a systematic way, the environmental aspects and impacts of product systems, from raw material acquisition to final disposal, in accordance with the stated goal and scope". LCA process is divided in 4 steps: goal and scope definition, inventory analysis, impact assessment, and interpretation, all phases being interacting and conducted according to an iterative process of improvement.

### 2.3.1 GOAL AND SCOPE DEFINITION

The goal of the present LCA was to determine the environmental burdens and their range of variation for 5 contrasted viticultural TMRs representative of the regional diversity, and to identify the environmental hotspots relatively to two Functional Units (FUs): 1ha of productive vineyard surface cultivated during one year and 1 kg grapes. The results are of interest to regional extension officers, winegrowers, and viticulture and LCA scientific communities.

LCA was performed with system boundaries from cradle to field gate because the aim is grape production process improvement. Therefore the system included all viticultural processes (technical operations) occurring during the assessed year of production, including the harvesting of the grapes, and during the non-productive phases and occasional operations. The system encompassed workers and machines transport from farm to the vineyard, transport of inputs from their production site to the vineyard. Soil rest duration was fixed to 3 years and modeled with identical practices for the 5 TMRs, on the basis of real practices of the winegrowers (barley cultivation). All vineyard activities during the non-productive phases (planting, including rooted cuttings production, early production phase and destruction) and the related transports, and all occasional activities in the vineyard (e.g. compost spreading, trellis maintenance) were amortized on the basis of a 30 year production life of the vineyard according to their frequency of occurrence in the assessed TMR (Figure 23). The life duration of the vineyard was estimated by expertise, while no statistical data were available on this question for the area.

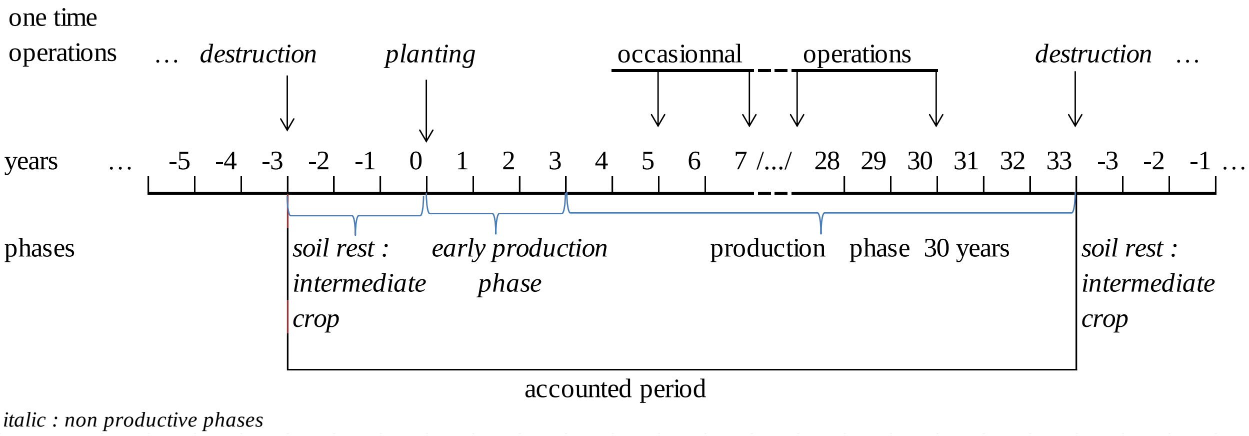


*Figure 23: phases and one-time operations of the vineyard life included in the system boundaries*

Concerning the second order limits, based on the Ecoinvent database methodology (Nemecek and Schnetzer 2011), for each input and machine, the raw materials, the energy and their production phase were considered as well as the capital goods and the materials production necessary for their elaboration.

### 2.3.2 LIFE CYCLE INVENTORY

The life cycle inventory (LCI) identifies emissions and extractions by a description of materials, energy, and pollutants fluxes that cross the system (Jolliet et al. 2010b) .

Data associated with each unit process of the TMRs were collected by interviewing the winegrowers and from their traceability documents. A detailed list of their equipment, dates and duration of operations, and inputs quantities used was established. Secondary data collection about equipment and inputs characteristics is the most time consuming step of LCI. The main sources were inputs and machinery manufacturers and dealers, reference documents concerning machines or PAI.s characteristics (e-phy 2013; Gazzarin and Vögeli 2011) and Ecoinvent database reports (Nemecek and Kägi 2007). Background data concerning input manufacturing and energy production, road infrastructures, were from the Ecoinvent 2.2 life cycle inventory (LCI) database (Frischknecht et al. 2005). The aim of the study being to assess types of TMR and practices represented by real cases, a number of assumptions were made to define standard values for data that were either too uncertain or too difficult to estimate by the winegrowers and/or that were not supposed to differentiate the TMRs types as diesel consumption per operation, distance from farm to vine plot or water quantity for sprayer washing for example. Table 15, lists the type of data, the values taken and the sources.

Unlike industrial LCAs, agricultural LCAs demand the use of models to estimate direct emissions of pollutants, due to the complex phenomena occurring in the plant-soil-water-air system. Direct emissions were calculated according to the following models, to be the closest to site and crop conditions within the available models applicable in LCA context as recommended by Bessou et al. (2012) and Benedetto et al. (2013).

Nitrogen from fertilizers and manure is emitted in various forms and in different compartments of the environment. $NH_3$ volatilization to the air, contributes to acidification and the eutrophication of sensitive ecosystems (Nemecek et al. 2011). We calculated it according to EMEP/EAA 2013 guidelines (Hutchings et al. 2013) Tier2, by multiplying a volatilization coefficient specific to each fertilizer type -from (Hutchings et al. 2013) for mineral fertilizers and (Koch and Salou 2014) for organic ones- by the applied quantity of N for mineral fertilizers and of TAN (total ammoniacal nitrogen) for organic fertilizers.

$N_2O$ is a high impact greenhouse gas (Nemecek et al. 2011), its emissions were modelled according to Nemecek et al. (2011) and IPCC (2006) , the formula includes direct emissions from fertilizers and crop residues (here from vine and/or cover crop), and induced emissions from emitted $NH_3$ and leached $NO_3^-$.

*Table 15: Origin of the life cycle inventory data*

| **Object** | | **data type** | | | **data origin** |
|---|---|---|---|---|---|
| | | standard | real | Calculated | |
| **distances** | estate headquarters-field | 1 km | | | estimate |
| | manual workers transport from estate headquarters to field per hour of work | 0.25 km | | | estimate (2 persons in 1 car, 1 go and return on 1 km for 4 hours work) |
| | Agricultural service provider's headquarter-field | 27.6 km | | | average of real distances for the 5 cases |
| **sizes** | Plot | 100mx100m | | | Estimate |
| **Input quantities** | water for sprayers and tractor washing | 45 l inside, 45 l + 50 l outside | | | IFV(2010) |
| | diesel per hour of operation | specific per type of operation | | | Gaviglio, C. (2010), Nemecek and Kägi (2007), winegrower. |
| | time for coupling and uncoupling machines to tractor | 18 mn for 10 ha | | | estimate from winegrowers data |
| | PAI.s and fertilizers | | X | | Winegrower |
| | duration of operations | | X | | Winegrower |
| **types and characteristics** | Machines | | X | | vine grower + secondary data |
| | Tractors | | X | | vine grower + secondary data |
| | PAI.s | | X | | vine grower + secondary data |
| | Fertilizers | | X | | vine grower + secondary data |
| | trellis infrastructure | | X | | vine grower + secondary data |
| | other inputs | | X | | vine grower + secondary data |
| **environment characteristics** | soil | | X | | direct measurements + existing cartography |
| | climate | | X | | closest weather station, real year dataset |
| **Direct emissions** | Field emissions from inputs or already present pollutants | | | X | Calculations with models specific to each substance chosen to account for crop and site specific conditions |

$NO_3^-$ is leached to groundwater by water from precipitation or irrigation, when they exceed plants (vine + cover crop) uptake primarily in autumn and winter. Modelling of $NO_3^-$ emissions is based on empirical models and is complex due to the different phenomena occurring in the soil. The possible presence of a cover crop under the vineyard interferes with the process of $NO_3^-$ leaching, by absorbing N during the dormancy period of the vine. The SQCB model (Faist Emmenegger et al. 2011) was used to calculate leached quantities of $NO_3^-$. Uptake by the cover crop could not be included in the present state of the model.

$NO_x$ emissions result from denitrification process, and occur in parallel of $N_2O$ emissions, they were modelled as 21% of $N_2O$ emissions (Nemecek et al. 2011)

Erosion of vineyard soils generates soil loss, and causes concomitant emission of various elements adsorbed on soil particles like heavy metals, phosphorus or pesticides. Erosion was calculated with the adaptation of Rusle2 model (Foster 2005b) to French conditions done in the AGRIBALYSE® agricultural LCI project (Koch and Salou 2014)

Phosphorus compounds contribute to eutrophication. Phosphate lixiviation and run-off and phosphorus emissions through erosion were calculated with SALCA-P model (Prasuhn 2006) using the Rusle2 erosion results mentioned above.

Heavy metal emissions to surface and ground water, and soil accumulation were calculated with SALCA-SM model (Freiermuth 2006), partly adapted to the French context for the AGRIBALYSE® project (Koch and Salou 2014). The model is based on the flow balance between heavy metal inputs from fertilizers, pesticides and atmospheric deposition, and outputs through grapes, and emissions, the remainder being considered as accumulated in the soil. 100% of heavy metals contained in pesticides are considered being deposited on the soil.

PAI. emissions to air, surface water, ground water and nearby agricultural soil, are important contributors to ecotoxicity (Bellon-Maurel et al. 2014). Complex transfer processes are involved (van Zelm et al. 2014) dependent primarily on PAI. properties, climatic and spraying conditions and plant and soil characteristics. They were calculated here with a specific version of the PestLCI 2.0 model (Dijkman et al. 2012), customized for viticulture (Renaud-Gentié et al. 2014b) by including the soil, climate and PAI. datasets of the TMRs of the present study as well as different vineyard sprayer drift curves and the effect of the cover-crop on PAI. emissions. PestLCI 2.0 calculates the quantities of PAI.s emitted from a virtual parallepiped including the plot and 1 m of soil under it and 100 m air above it. Still, Pest-LCI 2.0 only handles organic PAI.s, for this reason, sulfur, copper, and several other inorganic PAI. emissions were not calculated with this model (see table T1 in supplementary material).

$CO_2$ emitted from limestone applications was calculated by multiplying applied quantities by substance-specific emission factors (IPCC 2006).

Carbon and energy exportation in the grapes were accounted for as the system was limited to field gate, and winemaking and consumption were not included in the system. This carbon was considered as neutral for climatic change (Koch and Salou 2014) and calculated according to (Nemecek and Kägi 2007).

Finally, emissions of exhaust gases related to the use of the motorized machines - mainly tractors- were accounted for following the calculation method used in Ecoinvent (Nemecek and Kägi 2007). All substance emissions are directly proportional to diesel consumption except HC-, $NO_x$ and CO emissions which are obtained by (Nemecek and Kägi 2007) from load spectra specific to each process. These three emission components were determined in our study by assimilating each vineyard process to the most approaching Ecoinvent agricultural process.

### 2.3.3 CHARACTERIZATION METHODS FOR IMPACTS CALCULATION AND IMPACT CATEGORIES

Life cycle impact assessment (LCIA) links inventory data to environmental damages (endpoint) by modeling and aggregating impact pathways of substances (Jolliet et al. 2010b). However, due to uncertainties associated to quantification of damages on human health or environment, midpoint categories, which are considered to be links in the cause-effect chain of an impact category prior to the endpoints (Pieragostini et al. 2012) and which correspond to real phenomena like “eutrophication” are often preferred by LCA scientists. We worked in the present study with midpoint indicators to limit uncertainty of the results.

LCIA was carried out with SimaPro (version 8.03.14) software, and using a combination of different LCIA methods. For Freshwater Eco-toxicity (FwEtoxP), we chose USEtox™ (Rosenbaum et al. 2008). Developed as a scientific consensus model, it is supposed to represent the best application practice for characterization of toxic impacts of chemicals in LCA (Hauschild et al. 2008). Its FwEtoxP characterization factors database was enhanced with 18 missing pesticide ai.s for viticulture, specifically calculated for this study (Renaud-Gentié et al. 2014b). SALCA (Gaillard and Nemecek 2009) was applied for other impacts. The latter characterization method was developed specifically for agricultural LCAs by the AGROSCOPE LCA team (Switzerland) by selecting inventory impact categories (quantity of resources used) and mid-point impact categories from different existing characterization methods (IPCC 2007, EDIP 2003 and CML 2001). Additionally, the CML 2001 (Guinée et al. 2001) LCIA method was used for the comparison with results of other wine-sector LCA studies. The choice of impact categories for grapes LCIA Table 16) was done in accordance with main environmental issues of wine grape production (Renaud et al. 2011). Despite the relevance of human toxicity, the lack of USETox$^{TM}$ characterization factors for more than half of PAI.s used in this study prevented us from using this impact category.

Another set of impacts from the CML2001 method was calculated consistently with other grape or wine LCA studies (Vázquez-Rowe et al. 2012b; Villanueva-Rey et al. 2014a; Fusi et al. 2014a; Neto et al. 2012; Point et al. 2012; Gazulla et al. 2010; Benedetto 2013) to allow comparisons: Ozone Layer Depletion Potential (OLDP) (kg CFC-11 eq), Photochemical Oxydation Potential (POP) (kg $C_2H_4$ eq), Acidification Potential (AP) (kg $SO_2$ eq), Eutrophication Potential (EP) (kg$P_2O_5$), Abiotic Depletion Potential (ADP) (kg Sb eq) data related to common system boundaries were selected for comparison (grape production phase).

*Table 16: Impact categories selected for the study and corresponding characterization methods*

| Impact categories | Abbreviation (unit) | Characterization methods | Definition |
|---|---|---|---|
| Global warming potential at 100 years | GWP 100a (kg $CO_2$ eq) | IPCC 2007/ SALCA | Global warming due to greenhouse gases emissions ($CO_2$, $CH_4$, $N_2O$,…) modeled at a 100 years term |
| Photochemical ozone formation potential | POFP (veg) ( m2.ppm.h) | EDIP 2003/ SALCA | From precursors like $NO_x$, COV et $HO_x$, air pollutant, harmful for man, fauna and flora. (expressed in effect on vegetation) |
| Acidification potential | AP ($m^2$) | EDIP 2003/ SALCA | Caused by gases like $SO_2$, $NO_x$, HCl…gives acid rains and soil fertility losses. |
| Nitrogen caused aquatic eutrophication potential | AEP-N (kgN) | EDIP 2003/ SALCA | Excessive enrichment of surface waters in organic and mineral N-nutrients causing rapid growth of algae and cyanobacteria which deplete the oxygen supply and unbalance the rest of the ecosystem |
| Terrestrial Ecotoxicity potential* w/o pest at 100 years | TEtoxP. 100a*, (kg 1,4-DB eq) | CML 2001/ SALCA | Toxic effects of chemical substances, except pesticides*, but including heavy metals on terrestrial ecosystems, modelled at a term of 100 years |
| Fresh water Ecotoxicity potential | FwEtoxP (CTUe) | USETox$^{TM}$ (sensitivity) | Toxic effects of chemical substances on fresh surface water ecosystems results divided in R for “Recommended” and I for “Iinterim” according to the reliability of the PAI.s characterization factors (interim being more uncertain). |
| Abiotic resources consumption | Res (kg) | EDIP 2003/ SALCA | Consumption of non-renewable resources (minerals, metals, natural gaz, oil, coal) |
| Land competition | LC ($m^2a$) | Inventory/ SALCA | surface of land used (direct and indirect use) |
| Total water use (blue water) | WU ($m^3$) | Inventory/ SALCA | quantity of blue water used (direct and indirect) |

*Pesticides have been excluded from this impact calculation except those containing heavy metals (copper-based ingredients and Mancozeb) because the calculated emissions to soil out of the technosphere were negligible compared to emissions to air and groundwater (Renaud-Gentié et al. 2014b), moreover, According to ILCD guidelines (European Commission Joint Research Centre 2010), pesticides emissions to soil shouldn’t be accounted within the technosphere (cultivated field) except for accumulating substances like heavy metals.

## 2.4 DESCRIPTION OF SITE SPECIFIC CHARACTERISTICS

### 2.4.1 SOILS

We described the soil layers by field observation with a soil auger (by a soil scientist) and two soil samples (0-30cm and 30-60cm) were analyzed, the observation was consolidated with a comparison to existing detailed soil cartography of vineyard soils of the Middle Loire Valley provided by the regional service of characterization of viticulture terroirs (CTV) see Table T2 in supplementary material.

### 2.4.2 CLIMATE

Climate data needed for direct emissions modelling were obtained for each plot from the most accurate Météo France weather station among the closest ones (Table T3 in supplementary material),

The case study was done on the 2011 production year (from Oct1st 2010 to Sept 30th 2011). This vintage, in comparison to the average of 30 years 1981-2010, (Angers-Beaucouzé weather station) was slightly warmer (+0.2° on the annual average) especially in spring, it was much drier especially during the vine growing season (-60 mm rain and + 40 mm ETP for the April-September period on an average total of 306 mm rain for this period and 658 mm ETP) (Renaud-Gentié et al. 2014c).

For calculation of direct emissions during the non-productive phases, i.e. three first years of the vineyard, average climate data for three consecutive and contrasted years (2010-2011-2012) were taken in order to improve representativeness.

### 2.4.3 VINEYARDS

According to PDO rules, the studied plots present common characteristics: vertical shoot positioned canopy with minimum canopy height fixed to 0.6 x the inter-row distance, minimum plantation density of 4000 vines/ha, maximum 14 buds/vine and yield limited to 8 or 10t/ha according to the PDO related to this study (République-Française 2011c, a) Table 17 reports the main characteristics of the five TMRs.

*Table 17: Characteristics of the 5 vineyard plots studied for the 5 Technical Management Routes (TMRs)*

| Case | Slope % | Drainage | Cover crop extent in % surface and *density* | Soil tillage | Planting density (plant/ha) | Pesticide applications*2011 | Yield 2011 (kg/ha) |
|---|---|---|---|---|---|---|---|
| TMR 1 | 5 | No | 70% *high* | no | 4700 | 1H+4F+1I | 6440 |
| TMR 2 | 6 | No | 30% *average* | no | 5000 | 1H+6F+1I | 5250 |
| TMR 3 | 3 | No | 50% *average* | no | 4884 | 2H+3F+0I | 7500 |
| TMR 4 | 4 | Yes | 50% *average* | yes | 4000 | 0H+5F+2I | 5880 |
| TMR 5 | 6 | No | 30% *average* | yes | 5000 | 0H+7F+0I | 5250 |

*H: herbicide, F: fungicide, I: insecticide

# 3 RESULTS

## 3.1 COMPARISON OF ECO-EFFICIENCY ASSESSMENT RESULTS OF THE 5 TMRS

The environmental performances of the TMRs are compared, for the two functional units (FU): “1ha of vineyard in production during one year”, and “1kg grapes” in Table 18 for the 9 impact categories. The data represented in relative percentages are available in Figs F1, F2 and F3 in supplementary material.

*Table 18: Life Cycle Assessment results: eco-efficiency related to functional units (FUs) “1 ha of productive vineyard during one year” and “1kg of grapes” for the 5 Technical Management Routes (TMRs)*

| | TMR1 | | TMR2 | | TMR3 | | TMR4 | | TMR5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Cluster represented | "Systematic chemical use and limited handwork" | | "Moderate chemical use" | | "Minimum synthetic treatments and interventions" | | "Organic moderate” | | "Organic intensive" | |
| Impact categories | FU 1ha | FU 1kg | FU 1ha | FU 1kg | FU 1ha | FU 1kg | FU 1ha | FU 1kg | FU 1ha | FU 1kg |
| GWP 100a (kg $CO_2$ eq) | 1212 | *0.19* | 1461 | *0.28* | 864 | *0.12* | 1290 | *0.22* | 1720 | *0.33* |
| POFP (veg) (m2.ppm.h) | 13 146 | *2.04* | 21 561 | *4.11* | 11 930 | *1.59* | 20 659 | *3.51* | 27 915 | *5.32* |
| AP (m²) | 188 | *2.92E-02* | 277 | *5.28E-02* | 120 | *1.60E-02* | 256 | *4.35E-02* | 337 | *6.42E-02* |
| AEP-N (kgN) | 6.11 | *9.49E-04* | 6.87 | *1.31E-03* | 4.67 | *6.23E-04* | 7.18 | *1.22E-03* | 7.20 | *1.37E-03* |
| TEtoxP 100a (kg 1.4-DB eq) | 1.74 | *2.70E-04* | 0.31 | *5.89E-05* | 0.82 | *1.09E-04* | 0.75 | *1.28E-04* | 0.56 | *1.07E-04* |
| FwEtoxP(CTUe) | 4500 | *0.70* | 5 202 | *0.99* | 5 817 | *0.78* | 4 962 | *0.84* | 3 300 | *0.63* |
| *FwEtoxP(CTUe) R* | 670 | *0.10* | 1 201 | *0.23* | 131 | *0.02* | 75 | *0.01* | 93 | *0.02* |
| *FwEtoxP(CTUe) I* | 3 830 | *0.59* | 4 001 | *0.76* | 5 685 | *0.76* | 4 887 | *0.83* | 3 207 | *0.61* |
| Res (kg) | 0.91 | *1.42E-04* | 0.48 | *9.19E-05* | 0.30 | *4.01E-05* | 0.55 | *9.30E-05* | 0.51 | *9.64E-05* |
| LC (m²a) | 12 199 | *1.89* | 14 927 | *2.84* | 12 659 | *1.69* | 13 079 | *2.22* | 14 394 | *2.74* |
| WU ($m^3$) | 8.82 | *1.37E-03* | 7.20 | *1.37E-03* | 3.50 | *4.66E-04* | 7.49 | *1.27E-03* | 6.99 | *1.33E-03* |

GWP 100a: Global warming potential at 100 years, POFP (veg): Photochemical ozone formation potential, AP: Acidification potential, AEP-N: Nitrogen caused aquatic eutrophication potential, TEtoxP 100a: Terrestrial Ecotoxicity potential w/o pest at 100 years, FwEtoxP: Fresh water Ecotoxicity potential, Res: Abiotic resources consumption, LC: Land competition, WU: Total water use (blue water)

**TMR3**’s impact values are less than 50% of the highest impact values for the 7 out of 9 categories for the 1ha FU, and even less when expressed per kg grapes. **TMR5** shows, for both FUs, a very good eco-efficiency for terrestrial and aquatic ecotoxicity potentials (TEtoxP 100a and FwEtoxP) (less than 40% of the highest impacts); but it has the highest impacts for Global warming (GWP 100a), Photochemical Ozone formation (POFP), Acidification (AP) and Nitrogen-due Aquatic Eutrophication (AEP-N) potentials. **TMR1** presents, for both FUs, the second best eco-efficiency for GWP, POFP, AP AEP-N and land competition (LC); however it shows the highest impact for TEtoxP 100a, and Resources consumption (Res) (twice the values of the other TMRs) and Water use (WU) to a lesser extent. **TMR 2** is the second most impacting TMR for all impact categories except TEtoxP 100a. Finally, **TMR 4** is in a middle position for GWP100a, POFP (veg), AP, TEtoxP 100a, and LC. For the other categories, it is either the third most eco-efficient TMR (FwEtoxP) or the fourth (AEP-N, Res, WU). Its middle position is even more frequent for the mass-based FU.

## 3.2 CONTRIBUTION OF THE PRACTICES TO THE IMPACTS

The contributions of the TMR parts to the impacts are presented for each impact category, in percentage relatively to the most impacting TMR, per ha FU and commented per group of impacts presenting similarities (Figure 24, Figure 26 and Figure 27). As all individual techniques could not be represented, the TMRs were split in the same 10 TMR main parts listed in the legends of the charts. However, more details of the individual operations for each TMR part can be extracted from the results, as shown in Figure 25 in the next page. The non-productive phases' operations were accounted separately in a single category except the trellis installation that was identified separately due to its high impact.

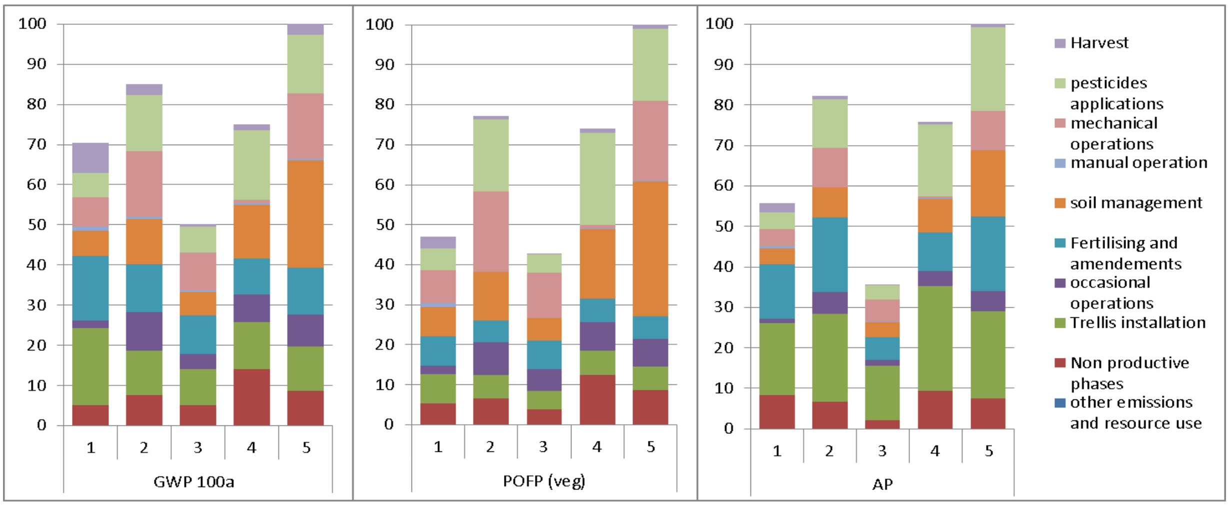


*Figure 24: Contributions of TMR parts to GWP 100a, POFP and AP impacts categories for the 5 TMRs, values in % of the most impacting TMR total impact.*

On the three charts, appear the differences between the TMR regarding their total impacts commented in section 3.1. The contributions to the impacts are distributed between many different TMR parts. Contributions of substances and single processes (including those from upstream in the life cycle) to each impact are provided by the LCA software, they contribute to explain the results presented here on the figures: on-farm diesel combustion contributed 37 to 61% to GWP 100a impact, followed by combustion of other fuels in upstream processes, fertilizers and compost processing and iron manufacturing. For all the TMRs, diesel combustion ($NO_x$ and NMVOC emissions) on farm contributed even more to POFP (veg) (more than 80%), followed by composting; diesel combustion also contributed significantly to AP. As the three impacts are highly influenced by diesel consumption on farm, they present very similar patterns of TMR hierarchy and TMR parts contributions.

Non-productive phases + trellis installation made a major contribution to the impacts in Figure 24, (up to 45% of AP impact of TMRs 1 and 4). Concerning GWP100a and POFP (veg), the non-productive phases were particularly contributive for TMR4 due to drainage installation which involves important mechanical operations (the other TMRs soils did not need drainage). The use of galvanized steel posts for trellis installation in TMR1 led to a high contribution of this TMR part because of steel manufacturing. However, it reduced the contribution of occasional operations because there was no need to replace posts during the life of the vineyard. Occasional operations contributed most for TMR2 because of machine operations linked to replacement of posts and renewal of plants. TMR1 had the highest contribution of fertilizers to GWP 100a, because of the use of chemical fertilizers. Fertilization operations impact directly on GWP 100a because of diesel consumption for application and due to $N_2O$ field emissions. Soil management contributed more for the two organic systems (TMR4 and 5) because of more frequent mechanical operations than in other TMRs. For the three conventional TMRs herbicide application and grass mowing contributed to the impacts for this part (Figure 25).

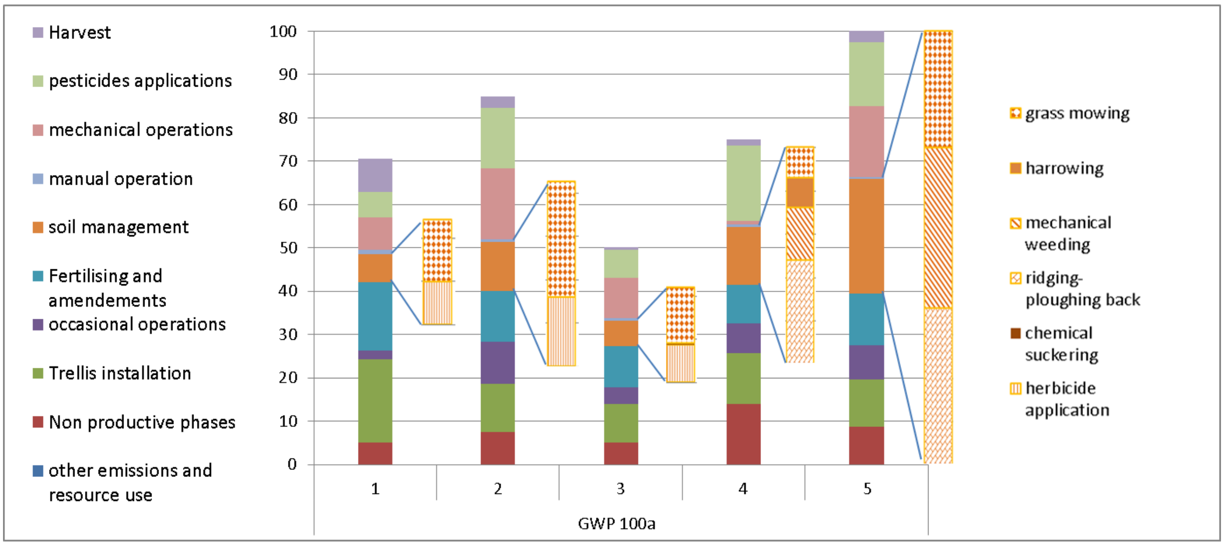


*Figure 25: detailed contribution of soil management practices to Global Warming Potential (GWP 100a) (details given in % of the most impacting soil management route) for the 5 TMRs, values in % of the most impacting TMR total impact.*

The very low contribution of mechanical operations (excluding soil management and pesticide applications) to the impacts of TMR4 was due to an absence of mechanical shoot trimming thanks to manual canopy management, well balanced vigor of the vines and a high trellis. This high trellis installation contributed more than for other TMRs to certain impacts such as AP; nonetheless the manual operations had very low impacts (only those due to workers transport to the field). The contribution of pesticide applications (fungicides + insecticides) was largest for TMR2, 4, and 5, due to the highest number of applications (7). The harvest contributed more for TMR4, the only TMR involving mechanical harvest.

AP impact showed the same tendencies as GWP 100a and POFP, because of the importance of emissions of acidifying gases by diesel combustion. However, it is also driven by zinc use for galvanization of trellising wires and emissions, due to N-fertilization, of $NH_3$, $N_2O$ and $NO_x$. This explains the importance of the contribution of trellis installation to this impact, and the higher contribution of trellis for TMRs using only steel wires, such as TMRs 2, 4 and 5. TMR3 and 1 use polyester wires for half of the trellis. The TMRs involving more organic fertilizers showed higher contributions of fertilization.

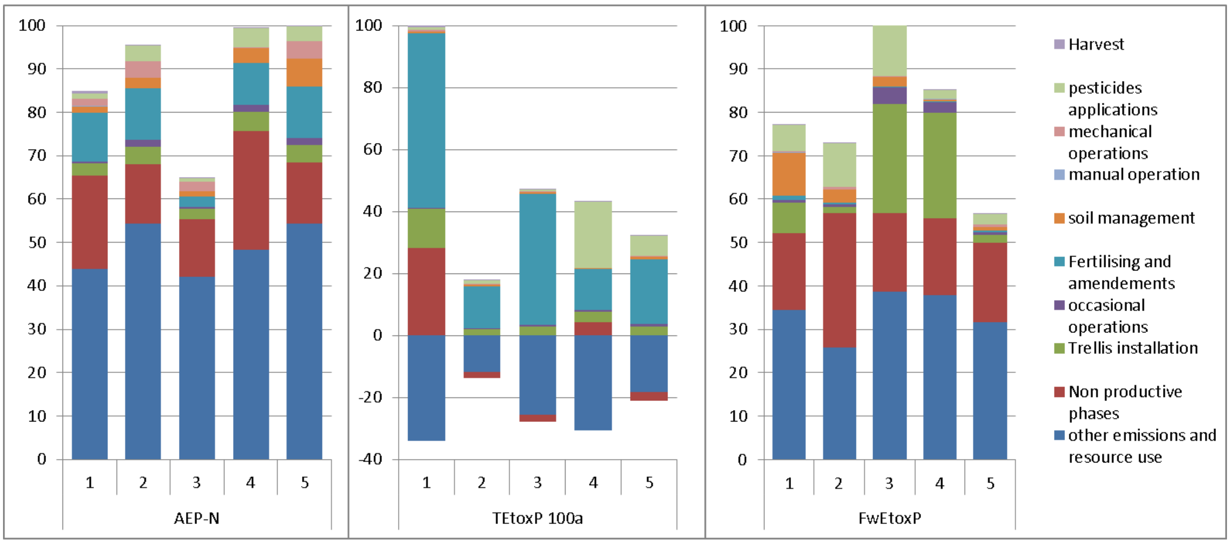


*Figure 26: Contributions of TMR parts to AEP-N, TEtoxP-100a and FwEtoxP impacts for the 5 TMRs values in % of the most impacting TMR total impact (distinction between Recommend and Interim characterization factors results for FwEtoxP is available in supplemental data figure F3)*

The AEP-N, TEtoxP-100a and FwEtoxP impacts (contributions detailed in Figure 26), showed different patterns than the previous three impacts. They have in common their relation to ecosystems health, the important contributions of “other emissions and resource use”, which cannot be attributed to any TMR part specifically, and the important role played by the inputs used on field.

The AEP-N impact category was mostly driven by N emissions from the soil directly or in-directly related to fertilization. TEtoxP-100a was mainly linked here to fertilization and the use of zinc for galvanization of wires and posts. FwEtoxP was more related to on-field pesticide emissions than the two previous impact categories, but also to heavy metal emissions from the soil not directly related to the practices.

The contributions of “other emissions and resource use” are the highest in AEP-N, and are mainly due to nitrate emissions. The higher the yield (increasing plant N-uptake), the lower the nitrate emissions calculated by the SQCB model, TMRs 1 and 3 showed hence the lowest contributions of “other emissions and resource use”. A part of non-productive phase contributions is also due to these emissions not directly linked to a practice, occurring during the non-productive phases. However, manure brought at planting (non-productive phases) and fertilization during vineyard life contributed also to AEP-N, but to a lesser extent. The other operations played a minor role for this impact mainly through $NO_x$ emissions from diesel combustion. TMR3 showed the best eco-efficiency with very low fertilizer applications and lower diesel consumption than the other TMRs.

TEtoxP-100a showed a specific pattern, with a negative part of the impacts. This negative part was related to heavy metals taken up by the plants from the soil and exported through the harvested grapes or removed from soils by lixiviation or runoff to water. The positive part of the impact was mainly due to heavy metals directly brought to the vineyard soil in fertilizers, manure at planting and limestone, and here, the differences between the fertilization practices in the five TMRs were obvious, TMR1 fertilization alternating limestone, composted pig manure and mineral fertilizer potentially released more heavy metals (mainly copper, zinc and lead) than the other fertilization programs (only composts and applied in lower quantities). The part related to trellis was again mainly due to zinc used for galvanization of steel wires (all) and posts (TMR1) and occurring during upstream processes. The impact of copper based fungi management for the two organic TMRs (4 and 5) contributed up to 50% of the impact (for TMR4).

FwEtoxP was mainly driven for all TMR by emissions of substances not directly related to the technical operations (in “other emissions and resource use” and in “non-productive phases”) and effect of the use of wood preservatives in the pine trellis posts manufacturing for TMRs 3 and 4. The use of PAI.s, cause differences between non organic (1, 2, 3) and organic TMRs (4 and 5) FwEtox with higher impact for non organic ones. Emissions occurring upstream in the pesticides life cycle represent the major part of pesticides application and soil management impact. In comparison, the effects of PAIs emitted from the field are small, even if TMR1 involved some PAI.s like Aclonifen (herbicide), and to a lesser extent, Fluopicolide and Cymoxanil, that are much toxic to Freshwater ecosystems.

The impacts Res, LC and WU were related to resources consumption (Figure 27). Res and WU are dominated by trellis, due to the use of zinc for galvanization of posts and wires (consumption of zinc natural resources and use of water for its extraction and processing).

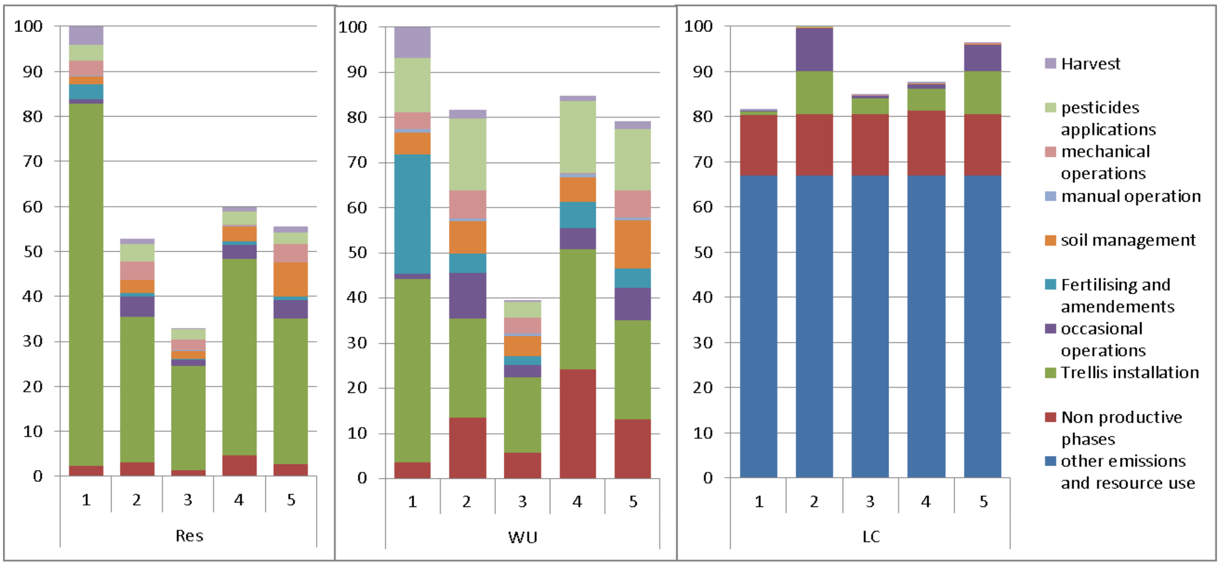


*Figure 27: Contributions of TMR parts to Resource and water use (Res and WU) and land competition (LC) impacts for the 5 TMRs, values in % of the most impacting TMR total impact.*

The use of galvanized steel posts in TMR1 contributed much to these two impacts. The quantity of galvanized steel wires used differentiated TMR 4 (8 wires per vine row) from TMRs 2 and 5 (4 wires per vine row) and TMR3 which showed the lowest Res and WU impact as it used using 2 galvanized steel wires and 2 polyester ones per vine row. Finally, the use of inorganic salt containing chromium for the treatment of pine wood posts contributed also to the Res impact for TMRs 3 and 4. The productive phases accounted for less than 40% of the Res impact and contributed to the use of agricultural machinery (crude oil consumption through diesel use and metals for machines manufacturing) with a similar pattern as for GWP100a, POFP and AP.

Direct WU was related to watering of young plants at planting and sprayer filling and washing for pesticide applications. Indirect WU was related to industrial use of water for zinc or oil extraction, or input production. The 5 TMRs showed important differences in WU. The productive phases contributed for less than 60% to WU. The manufacturing of chemical fertilizer in TMR1, the watering of young plants (non-productive phases) in TMR4 were the most water consuming operations after trellis manufacturing. TMR3’s good performance in WU was partly due to the use of rain water for treatments and sprayer washing but also to a low use of inputs and fuels, in contrast with TMRs 2 and 5.

Few differences between the TMRs can be seen on LC per ha. The main contributions to LC were identical for the 5 TMRs, they corresponded to the 1 ha needed directly cultivated for the year assessed and during the amortized non-productive phases. The marginal differences were due to the use of wood for trellis. These differences are explained by the nature, size and quantity of the posts involved in the “trellis installation” and “occasional operations” related to posts replacement. TMR1 had the lowest impact thanks to the use of metal posts. TMR2 was the least eco-efficient because of the replacement of approx.100% of the posts during the life of the vineyard (25 posts per ha per year).

# 4 DISCUSSION

### 4.1.1 TMRS ECO-EFFICIENCY HIERARCHY AND COMPARISON WITH OTHER PUBLISHED GRAPE PRODUCTION LCAS

The results of these five contrasted TMRs, representing the regional diversity of vineyard management, revealed major differences among the systems, which were only partly due to the conventional versus organic dichotomy.

In this 2011 production year, TMR3 (representing “Minimum synthetic treatments and interventions” cluster) was the most eco-efficient for most of the impacts for the two FUs (1 ha and 1 kg of grapes), except concerning FwEtox. The hierarchy of the other TMRs was less obvious, and depended on the relative weights given to the different impact categories. Focusing on climate change, air pollution, acidification and eutrophication, TMR1 (representing "Systematic chemical use and limited handwork") will come up as the second most eco-efficient after TMR3. But its high impacts on terrestrial ecosystems and resources are problematic. The same kind of dilemma occurs for TMR5 (representing “organic intensive” cluster), which shows low ecotoxicity and resource use, but high impacts on climate change, air pollution (POFP) and acidification. TMR4 (representing “organic moderate” cluster), offered the best example for organic viticulture TMR design with an average position for most impacts. Finally TMR2 (representing "Moderate chemical use" cluster), because of many operations and longer duration of machine use per operation, showed a low overall eco-efficiency coming frequently in fourth position. This global hierarchy of the TMRs based on eco-efficiency appeared rather consistent with the characteristics of the clusters defined in the initial typology presented in section 2.2., and that these TMRs represent. This typology was based on practices described by the winegrowers as generally implemented on the fields in the worst climatic years. TMR1 represents the cluster 1"systematic synthetic chemical use and limited handwork", it showed the highest terrestrial ecotoxicity. TMR2 represents the very eclectic cluster 2, "moderate chemical use", which was difficult to represent because of its low number of characteristic technical operations. TMR3 for cluster 3 "minimum synthetic treatments and interventions" gives eco-efficiency results very consistent with the cluster's name, this intervention-minimizing strategy proves to be the most rewarding of the five under study. The two organic TMRs also give results consistent with their cluster names: 4 "moderate organic" (i.e. with limited interventions) and 5 "intensive organic" (i.e. with many interventions), especially concerning GWP 100a, POFP (veg) and AP, with the limit that impacts due to sulfur application could not be assessed.

For the great majority of the impact categories, the hierarchy pattern between the TMRs doesn't change with the change of FU. The main reason is that TMR3 which presented the best eco-efficiency per ha also had the highest yield, which increased the gap with the others TMRs. The high yield of TMR1 comforted its good eco-efficiency for the first four impacts but the difference in yield with the other TMRs was not sufficient to suppress its high TetoxP and Res impacts.

The comparison with published wine or grape LCAs in the literature (Table 19) confirms the plausibility of the present results, situated in the range of most of the published data.

Compared to other oceanic climate viticultures like Rias Baixas, Galicia, Spain (Vázquez-Rowe et al. 2012b), Vinho Verde, Portugal (Neto et al. 2012) or Nova Scotia, Canada (Point et al. 2012), our results reveal very good eco-efficiency of Middle Loire Valley Chenin blanc vineyards, mainly due to a much lower diesel, pesticide and fertilizer use. Middle Loire Valley viticulture shows, like Ribeiro vineyards, Galicia, Spain, (Villanueva-Rey et al. 2014a), environmental performances close to Mediterranean climate vineyards like Rioja (Gazulla et al. 2010) or Sardinia (Benedetto 2013; Fusi et al. 2014a), where less fungal pressure is encountered. However, we must underline that 2011 vintage in Loire Valley presented low fungal pressure due to a dry spring. A less favorable vintage would lead to higher impacts per ha as shown by the data comparing different years of Villanueva-Rey et al. (2014) and (Vázquez-Rowe et al. 2012b) in Table 19 and our comparison of two contrasted vintages on TMR3 presented in (Renaud-Gentié et al. 2014c). FweTox is also much higher in Vazquez Rowe et al. (2012) and Villanueva-Rey et al. (2014) because of the use of the original caracteriztion factor (CF) found in UseTox database for Folpet, this CF was updated for the present study giving a much lower FwEtox potential for this substance (Renaud-Gentié et al. under review). On the basis of these results, we can assume that an increase of the potential impacts caused by a more humid year should not exceed 50% - except for FwEtoxP, which is very sensitive to the eco-toxicity potential of PAI.s. In such conditions the eco-efficiency of the TMRs under study would remain good compared to the literature. Nevertheless, the hierarchy presented in this paper between the five TMRs demands to be verified for a climatically difficult year before giving final conclusions on the relative eco-efficiency of the five clusters.

*Table 19: Comparison of eco-efficiency of 1 year productive phases (up to field gate) per FU (1kg grape).*

| | GWP 100a (IPCC 2007) | POP (CML 2001) | Acidification(CML 2001) | Eutrophication (CML 2001) | FwEtox (USEtox-sensitivity) | Abiotic depletion (CML 2001) |
|---|---|---|---|---|---|---|
| unit | kg $CO_2$ eq | kg $C_2H_4$ eq | kg $SO_2$ eq | kg$P_2O_5$ | CTUe | kg Sb eq |
| Current study (TMR1) | 0.12 | 2.63E-05 | 9.86E-04 | 8.54E-04 | 0,48 | 6.97E-04 |
| Current study (TMR2) | 0.22 | 4.38E-05 | 2.18E-03 | 1.12E-03 | 0.60 | 1.32E-03 |
| Current study (TMR3) | 0.08 | 6.93E-05 | 5.59E-04 | 4.70E-04 | 0.44 | 4.30E-04 |
| Current study (TMR4) | 0.14 | 3.63E-05 | 1.46E-03 | 8.26E-04 | 0.43 | 8.59E-04 |
| Current study (TMR5) | 0.26 | 6.23E-05 | 2.87E-03 | 1.19E-03 | 0.41 | 1.60E-03 |
| Benedetto et al (2013) | 0.17 | - | 1.19E-03 | 1.64E-04 | - | 1.60E-03 |
| Fusi et al. (2014) | 0.08 | 3.66E-05 | 8.09E-04 | 2.01E-04 | - | 6.00E-04 |
| Gazulla et al. (2010) | 0.40 | 2.36E-05 | 1.65E-03 | 2.40E-02 | - | - |
| Neto et al. (2012) | 2.00 | 3.10E-04 | 8.30E-03 | 7.30E-03 | - | 1.10E-02 |
| Point et al. (2012) | 0.57 | -1.43E-04 | 9.19E-03 | 4.28E-03 | - | 1.83E-03 |
| Vázquez-Rowe et al. (2012b) 2007 | 1.65 | 4.71E-04 | 1.08E-02 | 4.38E-03 | 29.44 | 5.00E-03 |
| Vázquez-Rowe et al. (2012b) 2008 | 1.89 | 5.42E-04 | 1.25E-02 | 5.17E-03 | 35.73 | 5.30E-03 |
| Vázquez-Rowe et al. (2012b) 2009 | 1.88 | 5.45E-04 | 1.22E-02 | 5.19E-03 | 42.31 | 5.09E-03 |
| Vázquez-Rowe et al. (2012b) 2010 | 1.55 | 4.42E-04 | 1.02E-02 | 4.06E-03 | 33.65 | 4.33E-03 |
| Villanueva-Rey (2014) bd. 2010 | 0.09 | 3.39E-05 | 8.00E-04 | 2.09E-04 | 0.32 | 5.64E-04 |
| Villanueva-Rey (2014) bd. 2011 | 0.06 | 2.55E-05 | 5.45E-04 | 1.55E-04 | 0.31 | 4.27E-04 |
| Villanueva-Rey (2014) bd-cv. 2010 | 0.13 | 6.64E-05 | 1.82E-03 | 3.18E-04 | 0.30 | 8.36E-04 |
| Villanueva-Rey (2014) bd-cv 2011 | 0.08 | 3.33E-05 | 8.91E-04 | 1.73E-04 | 0.20 | 5.00E-04 |
| Villanueva-Rey (2014) cv. 2010 | 0.34 | 1.64E-04 | 4.58E-03 | 2.08E-03 | 32.91 | 1.97E-03 |
| Villanueva-Rey (2014) cv. 2011 | 0.26 | 1.18E-04 | 3.47E-03 | 1.53E-03 | 15.73 | 1.49E-03 |

## 4.2 HOTSPOTS AND PRACTICES IMPROVEMENTS

The main environmental hotspots identified in all TMRs are on-farm diesel consumption and related emissions, trellis infrastructure mainly due to steel wire galvanization, but also to trellis posts production and transport, fertilizer production, on-field emissions related to fertilisation, and in a lesser extent, emissions of pesticides. Water use is very low in these non-irrigated situations (0.0013m$^3$ for 1 kg of grapes) compared to irrigated vineyards (0.1 m$^3$ for 1.1 kg of grapes (Fusi et al. 2014a)) and hence is not considered here as a hotspot.

Our results show, as Neto et al. (2012) and Villanueva-Rey et al. (2014a) that diesel combustion, in agricultural machinery is a major eco-efficiency concern for viticulture, contributing strongly to three impacts (GWP 100a, POFP (veg) and AP), and to a lesser degree to most others. The total annual on-farm diesel consumption of the 5 TMRs varied from 102 kg/ha (TMR3) to 286 kg/ha (TMR5) for the complete TMR, these consumptions appear low compared to literature data. (Vázquez-Rowe et al. 2012b) mentions consumptions up to 510 kg/ha/year only for productive phases and Fusi et al. (2014) mention 121 kg/ha for productive phases and 695 kg/ha for preproduction phases. However, the difference between these two contrasted TMRs suggests possible improvements for TMR5 in order to reduce diesel consumption. This can be thought through practices benchmarking between TMR3 and 5: for a similar operation needing a tractor, the time of work per ha of the tractor is significantly lower in TMR3 than TMR5 (30 to 50% less). For on-field operations demanding a low traction power, like herbicide application, or small transports, a quad replaces the tractor in TMR3, reducing considerably fuel consumption for these operations (1 l/h gasoline vs. 4 to 6 l/h diesel for a same operation). However, TMR5 being an organic system, mechanical weeding will inevitably require more diesel than quad herbicide application, unless horse traction is used. Horse pulled hoeing is hence developing in some organic vineyards; in comparison to mechanical hoeing, it proved to be highly advantageous regarding climate change, human health and resources consumption, but more water demanding and ecosystems impacting and doubling work time requirement (Naviaux et al. 2012). The use of biofuel as suggested by (Benedetto 2013) and of electric powered tractor recently released on the market should be assessed.

Trellis infrastructure is also a major contributor to impacts. Even if this operation is mainly done once at the beginning of the vineyard life, the winegrower renews yearly a part of the trellis and regularly replants vineyards in his estate and hence installs new trellis systems. The sensitivity analysis (Table 20) shows that at trellis installation, replacing galvanized steel tying-up wires by polyester ones greatly reduces resources depletion and acidification. It also facilitates canopy tying up manual work.

The choice of post type is more complex, inorganic salts and chromium based treatment of pine posts is eco-toxic and resource consuming, but galvanized steel presents other important impacts, particularly on resource use and as seen in the present study and mentioned by Point et al.(2012). The use of locally grown acacia posts permits to avoid toxic chemical wood treatment (Villanueva-Rey et al. 2014a) and reduces transport. The sensitivity analysis clearly showed the advantage of this solution compared to galvanized steel and even to treated pine on resource use. The gain due to locally grown trees compared to the same posts transported on 1800 km is visible on GWP.

*Table 20: analysis of sensitivity of LCA results to trellis system modifications, percentage of decrease of 3 impacts (Global Warming and Acidification Potentials and Resources use) compared to initial situation for the 5 Technical Management Routes (TMR)*

| TMR | Initial situation | | GWP 100a | | AP | | Res | |
|---|---|---|---|---|---|---|---|---|
| | Posts type* /transport distance | Wires* | local AW posts | local AW posts + 2 poly wires | local acacia posts | local AW posts + 2 poly wires | local AW posts | local AW posts + 2 poly wires |
| 1 | GS/650 km+ TPW/ 1800 km | 2 GS + 2 poly | -19% | - | **-27%** | - | **-76%** | - |
| 2 | AW/2300 km | 4 GS | **-10%** | **-10%** | -2% | **-14%** | -3% | **-30%** |
| 3 | TPW/ 1800 km | 2 GS + 2 poly | -5% | - | -3% | - | **-14%** | - |
| 4 | TPW/ 1800 km | 6 GS | -5% | -7% | -2% | **-22%** | **-11%** | **-48%** |
| 5 | AW/2300 km | 4 GS | -7% | -7% | -2% | **-11%** | -2% | **-28%** |

* GS: galvanized steel, TPW: treated pine wood, AW: acacia wood, poly: polyester

The importance of such non-productive step in LCA results are directly depending on the number of years of vineyard lifetime that are used for amortizing their impacts. This factor was standardized to 30 years for the 5 TMRs, but should be included with site specific data (which can only be a forecast) for an assessment of real situations oriented to advice or impact quantification for communication to clients for example.

Fertilization appeared as an important hotspot, as mentioned in other studies (Point et al. 2012), but is necessary to maintain the fertility potential of the soil and the production capacity of the vineyard. Moreover, the soils of all the TMRs under study present low organic matter contents, which need to be at least maintained and ideally increased. TMR3 uses local unprocessed distillery grape marc as a fertilizer, which limits transport and impacting processes as compost drying. Growing of legumes as green manure between the vine rows instead of grass will decrease the need for fertilizer; this is already partially done in TMR4 but not sufficiently to fully avoid fertilizing, nevertheless, species must be chosen carefully to avoid an increase of vigor of the vines, of water competition, or of workload due to cover renewal.

Concerning pesticide use, the winegrowers need to consider the human- and eco-toxicity potential of the PAI.s they are using, to be able to choose the less toxic ones. The present comparison shows that the vineyard can be protected at low eco-toxicological cost (TMR2 and 3) by avoiding some PAI.s like Cymoxanil, and Aclonifen (used in TMR1).

## 4.3 METHODOLOGICAL ISSUES

LCA, by including background processes and with its broad spectrum of impacts, permits to treat the environmental performances comparison in a, if not exhaustive, at least much broader approach than carbon footprint or local risk analysis-based approaches. Accordingly, LCA is a powerful method to identify environmental hotspots and point out the most eco-efficient vineyard management techniques. This study shows that the method can support decision on choosing farmer techniques and system design. However, LCA is a time consuming method requiring expertise. The development of a simplified calculation tool containing a large inventory database of viticulture techniques would allow a broader application of the method to advise individual winegrowers. As proposed by Bellon-Maurel et al. (2014) a life cycle inventory can partially rely on traceability data owned by the winegrowers, however this traceability is not homogeneously done in terms of tools and level of details. Getting accurate climatic and soil data at field scale remains also challenging for a field-scale-site specific approach.

$CO_2$ sequestration by the vine and cover crop during their lifetime was not included, as it is a temporary capture of carbon, and because most of the vine wood is burnt after vine destruction. $CO_2$ sequestration and release due to land use change was not considered considering a relative stability of vineyards areas in the region (less than 0.5% change in area per year 1999-2011 (France-Agrimer 2010, 2013)) and the lack of data concerning the nature of land transformation into or from vineyards in the region. The effect of change of viticultural practices on the entire life of the vineyard could not be accounted for due to lack of historical data on practices.

The importance of accounting for non-productive phases, including trellis, in viticulture eco-efficiency assessment as recommended by (Cerutti et al. 2014; Bessou et al. 2013; Benedetto et al. 2013) is confirmed by the part these elements take in the impacts and by the differences of impacts between the TMRs for these phases. The annual practices for the entire life of the vineyard (production years) were not included here for two main reasons; first the unavailability of such data given the length of vineyard life, and second and main reason, given our objective to support decision aid regarding farmer practices and system design for present and future systems, accounting for past practices would present a very limited interest. For the same reasons, a decrease of yield in the last years of the vineyard was not considered. Nevertheless, the annual variability in practices and yield caused by climatic conditions is a factor that needs to be seriously considered in studies aiming to provide references to farmers or consumers on average eco-efficiency of a type of TMR or a type of wine.

Climatic conditions influence the yield and the intensity of interventions by the farmers, but, together with soil characteristics, they also influence direct emission patterns as summarized in Table 21 shows also which emissions contribute to each impact category. GWP 100a, Res, LC, and WU impact categories are independent from site-specific conditions; accordingly, this part of the TMRs and practices eco-efficiency is applicable in any climatic and soil situation. The other categories are highly linked to the climatic conditions of the vintage or the soil type. The eco-efficiency conclusions concerning these impacts need to be linked to these particular situations.

*Table 21: Types of factors influencing direct emission quantities calculation as they are accounted in the present LCA and impact categories accounting for these emissions*

| | | $NO_3$- direct emissions | Pesticides direct emissions | Heavy metals direct emissions | direct emissions of P | direct emissions of $NH_3$, $N_2O$, $NO_x$ | diesel combustion direct emissions |
|---|---|---|---|---|---|---|---|
| Natural factors | climate | X | X | X | X | | |
| | soil characteristics | X | X | X | X | | |
| | Slope: % and length | | X | X | X | | |
| Anthropic factors | vine and cover-crop shape | | X | | | | |
| | mechanical. & manual. operations | | X | | | | X |
| | inputs | X | X | X | X | X | |
| others | grape yield | X | | X | | | |
| Impact categories accounting for each emission | GWP 100a (kg $CO_2$ eq) | | | | | X | X |
| | POFP (veg) ( m2.ppm.h) | | | | | X | X |
| | AP (m²) | X | | | | X | |
| | AEP-N (kgN) | X | | | | X | |
| | TEtoxP 100a, (kg 1,4-DB eq) | | | X | | | |
| | FwEtoxP (CTUe) | | X | | | X | X |
| | Res (kg), LC (m²a), WU ($m^3$) | | | | | | |

Further methodological developments are needed to complete the broad panorama of vineyard management eco-efficiency given by this study, and to increase the accuracy of some of the presented results: i) given the importance of diesel use in the environmental impacts, the database of fuel consumptions per vineyard management operation needs to be consolidated. We had to base a part of the study on estimates that need to be confirmed by more reliable data. Bellon-Maurel et al. (2014) recently released an extension to the previously published list of fuel consumption according to operations, but the sensitivity of fuel consumption to eco-driving, slope and speed of the tractor should be further investigated for an exhaustive quantification of their impact on diesel consumption variability for each practice; ii) nitrate emissions play a major role in AEP-N impact, however, the SQCB model used here for their quantification gives a global estimate of leaching but a model parameterized on vine, accounting for annual dynamics, cover crop presence and climatic conditions in nitrate leaching would permit a more site-specific approach; iii) human toxicity assessment is an important question to be addressed in the near future but needs further methodological developments (many characterization factors for PAI.s used in viticulture are lacking in the available databases) before it can be included ; iv) eco-toxicity assessment is still incomplete for the only emission and impacts calculations models available are not designed to handle inorganic chemicals; new models are needed for this purpose; v) inclusion of impacts categories accounting for soil quality and for biodiversity would permit a more comprehensive assessment however, they need to be designed for viticultural context; vi) the results were, here, related to two functional units: 1 kg grapes, as most of the published wine LCAs, and 1ha of productive vineyard cultivated during 1 year, as most of the published agricultural LCAs. The latter is more adapted to practices comparison, choice and design, which is the aim of this study. However, a quality-based functional unit would be of great interest in eco-efficiency driven choice of vineyard management techniques because the main function of grape production is not only the production of a grape quantity, but also the production of grapes of a given quality standard, specifically in PDO context. This will be the subject of the second part of this paper; vii) this work reveals the important variability of eco-efficiency corresponding to a real regional diversity of TMRs for a same cultivar and a same type of wine. This variability must be taken into account in the constitution of regional or national life cycle inventory databases of grape production for reporting in Environmental Product Declarations.

# 5 CONCLUSION

In the wine sector, LCAs had aimed either to support eco-labelling or to identify environmental hotspots in the production process, from a single wine on a single farm to regional or international comparisons including production systems comparisons (Benedetto et al. 2013; Vázquez-Rowe et al. 2012b). Many wine LCAs were conducted on the whole life cycle of a bottle of wine (Benedetto et al. 2013), unlike most agricultural LCAs that often are implemented "cradle to farm gate" because they aim to assess and improve the production stage (Hayashi et al. 2006a).

We illustrated, on a characterized diversity of vineyard Technical Management Routes, that LCA is a powerful method for eco-efficiency-based comparison of TMRs and technical choices at all stages of the TMR. Provided all phases of the vineyard life and site-specific conditions are considered, it permits to consider a broad spectrum of environmental impacts and to avoid pollution transfers from a TMR part to another, when improving a technique. However, it cannot be considered as a tool directly usable by production and transfer stakeholders without simplification of the framework and of the calculation tools based on the constitution of secondary data and processes databases.

The global approach of this work including a typology of TMR diversity before LCA gives a useful framework for characterization of eco-efficiency diversity at a territorial scale, useful for providing references to i) viticulture extension agents for accurate technical advising, ii) winegrowers to compare their eco-efficiency results to those of their colleagues, or iii) cooperatives to guide their vineyard technical policy.

The environmental hotspots and solutions identified will also be a useful base for the sound evolution of sets of rules of PDO or sustainability programs.

In the second paper, the question of inclusion of quality in LCA will be treated while remaining in the context of the assessment of the eco-efficiency of TMRs and practices.

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# ABBREVIATIONS

**Substances**

| | |
|---|---|
| $C_2H_4$ | Ethylene |
| CO | Carbon Oxide |
| HC | Hydrocarbon |
| N | nitrogen |
| $N_2O$ | dinitrogen oxide |
| $NH_3$ | ammonium |
| NMVOC | non-methane volatile organic compounds |
| $NO_3$- | nitrate |
| $NO_x$ | nitrogen oxides |
| $P_2O_5$ | Phosphorus pentoxide |
| $SO_2$ | sulfur dioxide |

**Impact categories**

| | |
|---|---|
| ADP | Abiotic Depletion Potential |
| AEP-N | Nitrogen caused aquatic eutrophication potential |
| AP | Acidification potential |
| FwEtoxP | Fresh water Ecotoxicity potential |
| GWP 100a | Global warming potential at 100 years |
| LC | Land competition |
| OLDP | Ozone Layer Depletion Potential |
| POFP (veg) | Photochemical ozone formation potential |
| POP | Photochemical Oxidation Potential |
| Res | Abiotic resources consumption |
| TEtoxP 100a, | Terrestrial Ecotoxicity potential w/o pest at 100 years |
| WU | Total water use (blue water) |

**Units**

| | |
|---|---|
| CTUe | comparative toxic unit for aquatic ecotoxicity impacts = PAF × m³ × day per kg substance emitted |
| kg 1,4-DB eq | 1,4-dichlorobenzene equivalents/kg emission |
| kg CFC-11 eq | kg Chloro fluoro carbon-11 equivalent/ kg emission |
| Kg $CO_2$ eq | kg carbon dioxide/kg emission |
| kg Sb eq | kg antimony equivalents/kg extraction |
| kg $SO_2$ eq | kg $SO_2$ equivalents/ kg emission |
| PAF | potentially affected fraction of species (PAF) |

**Others**

| | |
|---|---|
| FU | Functional Unit |
| PAI. | Pesticide active ingredient |
| TMR | Technical Management Route |

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# SUPPLEMENTARY MATERIAL

Table T1 Pesticide active ingredients applied on the 5 TMRs under study in 2011, vine stage and conditions of application.

| Plot | n° treatment* | pesticide | crop type | month | application rate (kg/ha) | application method | application method selected in PestLCI |
|---|---|---|---|---|---|---|---|
| TMR1 | Herbicide 1 | Aminotriazole=Amitrole | Grass I - all phases | April | 0,790 | sheltered herbicide boom | PestLCI 1 Soil Incorporation |
| TMR1 | Herbicide 1 | Aclonifen | Grass I - all phases | April | 0,307 | sheltered herbicide boom | PestLCI 1 Soil Incorporation |
| TMR1 | Fungicide 1 | sulfur | Vines II - h80% grass | May | 5,890 | recycling tunnel | |
| TMR1 | Fungicide 1 | Folpet | Vines II - h80% grass | May | 0,740 | recycling tunnel | Recycling tunnel |
| TMR1 | Fungicide 1 | Fosetyl-Al | Vines II - h80% grass | May | 1,473 | recycling tunnel | |
| TMR1 | Fungicide 2 | Fluopicolide | Vines II - h80% grass | May | 0,120 | Airblast, from top of the canopy, Paris titan | GRV IDK |
| TMR1 | Fungicide 2 | Fosetyl-Al | Vines II - h80% grass | May | 1,747 | Airblast, from top of the canopy, Paris titan | GRV IDK |
| TMR1 | Fungicide 2 | Proquinazid Technique | Vines II - h80% grass | May | 0,050 | Airblast, from top of the canopy, Paris titan | GRV IDK |
| TMR1 | fungicide 3 | Tetraconazole | Vines III - a80% grass | June | 0,030 | Airblast, from top of the canopy, Paris titan | GRV IDK |
| TMR1 | insecticide1 | Indoxacarbe=DPX MP062 | Vines III - a80% grass | June | 0,040 | Airblast, from top of the canopy, Paris titan | GRV IDK |
| TMR1 | Fungicide 4 | Copper (II) oxychloride | Vines III - a80% grass | June | 0,730 | Airblast, from top of the canopy, Paris titan | |
| TMR1 | Fungicide 4 | copper (II) trib Cu sulfate | Vines III - a80% grass | July | 0,183 | Airblast, from top of the canopy, Paris titan | |
| TMR1 | Fungicide 4 | Cymoxanil | Vines III - a80% grass | July | 0,122 | Airblast, from top of the canopy, Paris titan | GRV IDK |
| TMR1 | Fungicide 4 | Mancozeb | Vines III - a80% grass | July | 0,405 | Airblast, from top of the canopy, Paris titan | GRV IDK |
| TMR2 | herbicide 1 | Aminotriazole=Amitrole | Grass I - all phases | April | 1,603 | sheltered herbicide boom | PestLCI 1 Soil Incorporation |
| TMR2 | herbicide 1 | ammonium thiocyanate** | Grass I - all phases | April | 1,505 | sheltered herbicide boom | |
| TMR2 | herbicide 1 | Glyphosate | Grass I - all phases | April | 0,900 | sheltered herbicide boom | PestLCI 1 Soil Incorporation |
| TMR2 | fungicide1 | sulfur | Vines I - a30% grass | April | 6,400 | Pneumatic, side by side, Paris 800 | |
| TMR2 | fungicide2 | Méfénoxam= Metalaxyl-M | Vines II - a30% grass | May | 0,072 | Pneumatic, side by side, Paris 800 | CG: pneumatic sprayer side by side |
| TMR2 | fungicide2 | Mancozeb | Vines II - a30% grass | May | 1,150 | Pneumatic, side by side, Paris 800 | CG: pneumatic sprayer side by side |
| TMR2 | fungicide2 | Metrafenone=AC 375839 | Vines II - a30% grass | May | 0,085 | Pneumatic, side by side, Paris 800 | CG: pneumatic sprayer side by side |
| TMR2 | fungicide3 | sulfur | Vines II - a30% grass | May | 8,000 | Pneumatic, side by side, Paris 800 | |
| TMR2 | fungicide4 | disodium phosphonate | Vines III - a30% grass | June | 0,750 | Pneumatic, side by side, Paris 800 | |
| TMR2 | fungicide4 | Cyazofamid | Vines III - a30% grass | June | 0,080 | Pneumatic, side by side, Paris 800 | CG: pneumatic sprayer side by side |
| TMR2 | fungicide4 | Fenbuconazole | Vines III - a30% grass | June | 0,038 | Pneumatic, side by side, Paris 800 | CG: pneumatic sprayer side by side |
| TMR2 | fungicide5 | Metrafenone=AC 375839 | Vines III - a30% grass | June | 0,085 | Pneumatic, side by side, Paris 800 | CG: pneumatic sprayer side by side |
| TMR2 | insecticide 1 | Indoxacarbe=DPX MP062 | Vines III - a30% grass | June | 0,038 | Pneumatic, side by side, Paris 800 | CG: pneumatic sprayer side by side |
| TMR2 | fungicide6 | Fenbuconazole | Vines III - a30% grass | July | 0,038 | Pneumatic, side by side, Paris 800 | CG: pneumatic sprayer side by side |
| TMR3 | Herbicide1 | Glyphosate | Grass I - all phases | March | 0,540 | sheltered herbicide boom | PestLCI 1 Soil Incorporation |
| TMR3 | Herbicide1 | Aminotriazole** | Grass I - all phases | March | 0,920 | sheltered herbicide boom | PestLCI 1 Soil Incorporation |
| TMR3 | Herbicide1 | ammonium thiocyanate** | Grass I - all phases | March | 0,860 | sheltered herbicide boom | |
| TMR3 | Herbicide1 | Flazasulfron | Grass I - all phases | March | 0,020 | sheltered herbicide boom | PestLCI 1 Soil Incorporation |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| TMR3 | Herbicide2 | Glyphosate | Grass I - all phases | May | 0,090 | sheltered herbicide boom | PestLCI 1 Soil Incorporation |
| TMR3 | Fungicide 1 | Trifloxystrobin | Vines II - a50% grass | May | 0,060 | Pneumatic, side by side, Nicolas | ABMOST: pneumatic sprayer side by side |
| TMR3 | Fungicide 2 | Trifloxystrobin | Vines III - a50% grass | June | 0,060 | Pneumatic, side by side, Nicolas | ABMOST: pneumatic sprayer side by side |
| TMR3 | Fungicide 2 | Dimethomorph | Vines III - a50% grass | June | 0,180 | Pneumatic, side by side, Nicolas | ABMOST: pneumatic sprayer side by side |
| TMR3 | Fungicide 2 | Mancozeb | Vines III - a50% grass | June | 1,200 | Pneumatic, side by side, Nicolas | ABMOST: pneumatic sprayer side by side |
| TMR3 | Fungicide 3 | Difenoconazole | Vines III - a50% grass | July | 0,030 | Pneumatic, side by side, Nicolas | ABMOST: pneumatic sprayer side by side |
| TMR3 | Fungicide 3 | Meptyldinocap | Vines III - a50% grass | July | 0,210 | Pneumatic, side by side, Nicolas | ABMOST: pneumatic sprayer side by side |
| TMR4 | fungicide1 | Copper (II) trib Cu sulfate | Vines I - h50% grass | April | 0,220 | Airblast, vertical tangencial flux, Holder | |
| TMR4 | fungicide1 | Sulfur | Vines I - h50% grass | April | 7,920 | Airblast, vertical tangencial flux, Holder | |
| TMR4 | fungicide2 | Copper (II) trib Cu sulfate | Vines II - a50% grass | May | 0,220 | Airblast, vertical tangencial flux, Holder | |
| TMR4 | fungicide2 | Sulfur | Vines II - a50% grass | May | 7,920 | Airblast, vertical tangencial flux, Holder | |
| TMR4 | fungicide3 | Sulfur | Vines II - a50% grass | May | 7,920 | Airblast, vertical tangencial flux, Holder | |
| TMR4 | fungicide4 | Copper (II) trib Cu sulfate | Vines III - a50% grass | June | 0,140 | Airblast, vertical tangencial flux, Holder | |
| TMR4 | fungicide4 | Sulfur | Vines III - a50% grass | June | 7,920 | Airblast, vertical tangencial flux, Holder | |
| TMR4 | fungicide5 | Copper (II) trib Cu sulfate | Vines III - a50% grass | June | 0,140 | Airblast, vertical tangencial flux, Holder | |
| TMR4 | fungicide5 | Sulfur | Vines III - a50% grass | June | 9,900 | Airblast, vertical tangencial flux, Holder | |
| TMR4 | insecticide 1 | SpinosynA | Vines III - a50% grass | June | 0,038 | Airblast, vertical tangencial flux, Holder | GRV FanTip |
| TMR4 | insecticide 1 | SpinosynD | Vines III - a50% grass | June | 0,013 | Airblast, vertical tangencial flux, Holder | GRV FanTip |
| TMR4 | insecticide 2 | Pyréthrines** | Vines III - a50% grass | June | 0,030 | Airblast, vertical tangencial flux, Holder | GRV FanTip |
| TMR5 | fungicide 1 | copper (II) trib Cu sulfate | Vines I - a30% grass | April | 0,180 | Pneumatic, side by side, Paris 800 | |
| TMR5 | fungicide 1 | sulfur | Vines I - a30% grass | April | 4,000 | Pneumatic, side by side, Paris 800 | |
| TMR5 | fungicide 2 | copper (II) trib Cu sulfate | Vines II - a30% grass | May | 0,180 | Pneumatic, side by side, Paris 800 | |
| TMR5 | fungicide 2 | sulfur | Vines II - a30% grass | May | 4,000 | Pneumatic, side by side, Paris 800 | |
| TMR5 | fungicide 3 | copper (II) trib Cu sulfate | Vines III - a30% grass | May | 0,180 | Pneumatic, side by side, Paris 800 | |
| TMR5 | fungicide 3 | sulfur | Vines III - a30% grass | May | 4,000 | Pneumatic, side by side, Paris 800 | |
| TMR5 | fungicide 4 | copper (II) trib Cu sulfate | Vines III - a30% grass | June | 0,180 | Pneumatic, side by side, Paris 800 | |
| TMR5 | fungicide 4 | sulfur | Vines III - a30% grass | June | 4,000 | Pneumatic, side by side, Paris 800 | |
| TMR5 | fungicide 5 | copper (II) trib Cu sulfate | Vines III - a30% grass | June | 0,180 | Pneumatic, side by side, Paris 800 | |
| TMR5 | fungicide 5 | sulfur | Vines III - a30% grass | June | 4,000 | Pneumatic, side by side, Paris 800 | |
| TMR5 | fungicide 6 | sulfur | Vines III - a30% grass | July | 24,750 | Pneumatic, side by side, Paris 800 | |
| TMR5 | fungicide 7 | sulfur | Vines III - a30% grass | July | 24,750 | Pneumatic, side by side, Paris 800 | |

* a same treatment n° means the substances were sprayed at the same time and mixed int he same spraying mixture

**synonyms: ammonium thiocyanate = ammonium sulfocyanate, aminotriazole=amitrole, metalaxyl-M = metrafenone, pyrethrines = pyrethrum, Indoxacarbe=DPX MP062

In grey, the inorganic or partially inorganic pesticide ai.s which emissions couldn't be modeled in PestLCI2.0

Table T2: soil characteristics for the 5 cases studied

| | Unit | TMR1 | | | TMR2 | | | | TMR3 | | | | TMR4 | | | | | | TMR5 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Name | | UTB131-roche-schiste greseux à grès | | | UTB25-altérite-calcaire lacustre | | | | UTB35-Recouvrements de formations sénoniennes sur formations carbonatées du crétacé supérieur (Sénonien > 60 cm) | | | | UTB11-sable éolien sur altération de schiste | | | | | | UTB25-altérite-calcaire lacustre | | | |
| Horizon | | H1 | H2 | H3 | H1 | H2 | H3 | H4 | H1 | H2 | H3 | H4 | H1 | H2 | H3 | H4 | H5 | H6 | H1 | H2 | H3 | H4 |
| Start depth | m | 0 | 0.25 | 0.5 | 0 | 0.25 | 0.5 | 0.7 | 0 | 0.4 | 0.65 | 0.8 | 0 | 0.2 | 0.45 | 0.6 | 0.65 | 0.8 | 0 | 0.20 | 0.5 | 0.75 |
| End depth | m | 0.25 | 0.5 | 1 | 0.25 | 0.5 | 0.7 | 0.9 | 0.4 | 0.65 | 0.8 | 1 | 0.2 | 0.45 | 0.6 | 0.65 | 0.8 | 1 | 0.20 | 0.5 | 0.75 | 100 |
| Clay content (<2µm) | % | 15 | 15 | MR | 15 | 15 | 40 | 25 | 15 | 15 | 40 | 15 | 10 | 10 | 15 | 25 | 25 | MR | 15 | 15 | 40 | 25 |
| Silt content (2-50 µm) | % | 40 | 40 | MR | 20 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 35 | 35 | 40 | 40 | 40 | MR | 20 | 40 | 40 | 40 |
| Sand content (>50µm) | % | 45 | 45 | MR | 65 | 45 | 20 | 35 | 45 | 45 | 20 | 45 | 55 | 55 | 45 | 35 | 35 | MR | 65 | 45 | 20 | 35 |
| organic matter | % | 0.95 | 1.63 | 0 | 0.53 | 0.48 | 0.4 | 0.4 | 1.51 | 1 | 0.4 | 0.4 | 0.65 | 1.31 | 0.4 | 0.4 | 0 | 0 | 1.08 | 0.86 | 0.4 | 0.4 |
| content (method Anne) | % | 0,55 | 0,95 | | 0,31 | 0,28 | | | 0,88 | 0,58 | | | 0,38 | 0,76 | | | | | 0,63 | 0,50 | | |
| pH water | | 6.4 | 6.2 | 6.2 | 8.3 | 8.5 | 8.5 | 8.5 | 8.2 | 8.3 | 8.3 | 8.3 | 6.6 | 6.6 | 6.6 | 6.6 | 6.6 | 6.6 | 8.4 | 8.5 | 8.5 | 8.5 |

🟩 = estimate based on existing detailled terroirs carthography

MR = mother rock

Table T3 : weather stations used in the study

| Location | Latitude | Longitude | Elevation (m) | TMR covered |
|---|---|---|---|---|
| Beaucouzé | 47°28'42"N | 0°36'48"W | 50 | General |
| Fontaine-Guérin | 47°29'30"N | 0°10'00"W | 41 | 3 |
| Martigné-Briand | 47°15'06"N | 0°26'06"W | 74 | 2 and 5 |
| Beaulieu-S-Layon | 47°18'30"N | 0°35'48"W | 81 | 4 |
| Blaison-Gohier | 47°23'42"N | 0°21'24"W | 68 | 1 |

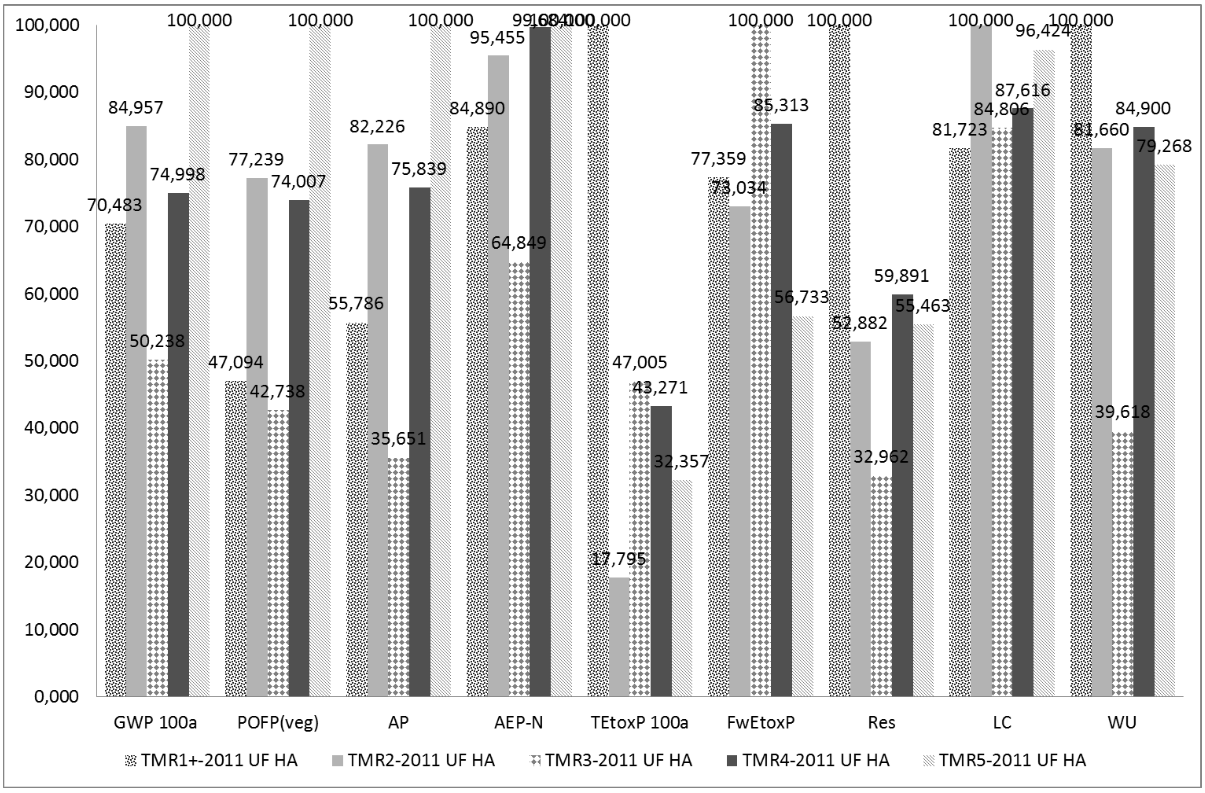

Figure F2 comparison of the 5 TMRs impacts per ha in % of the highest value.

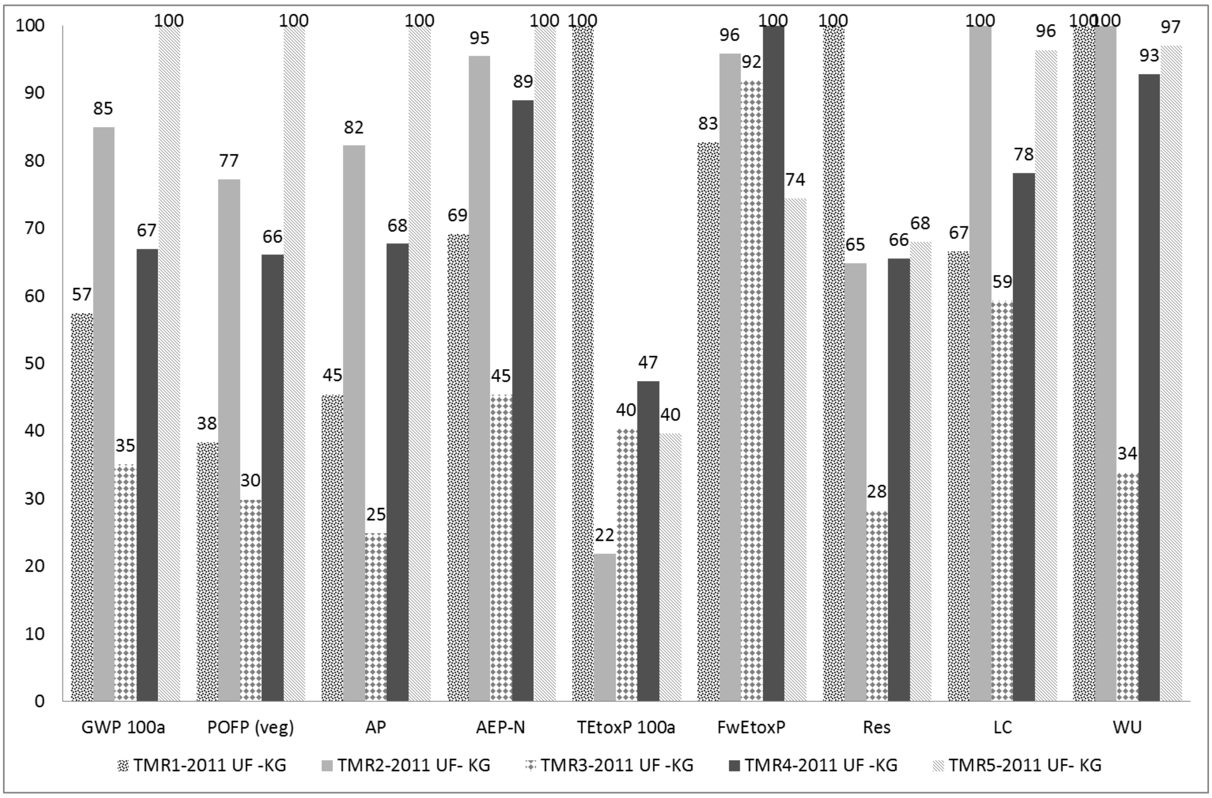

Figure F3 comparison of the 5 TMRs impacts per kg grapes in % of the highest value.

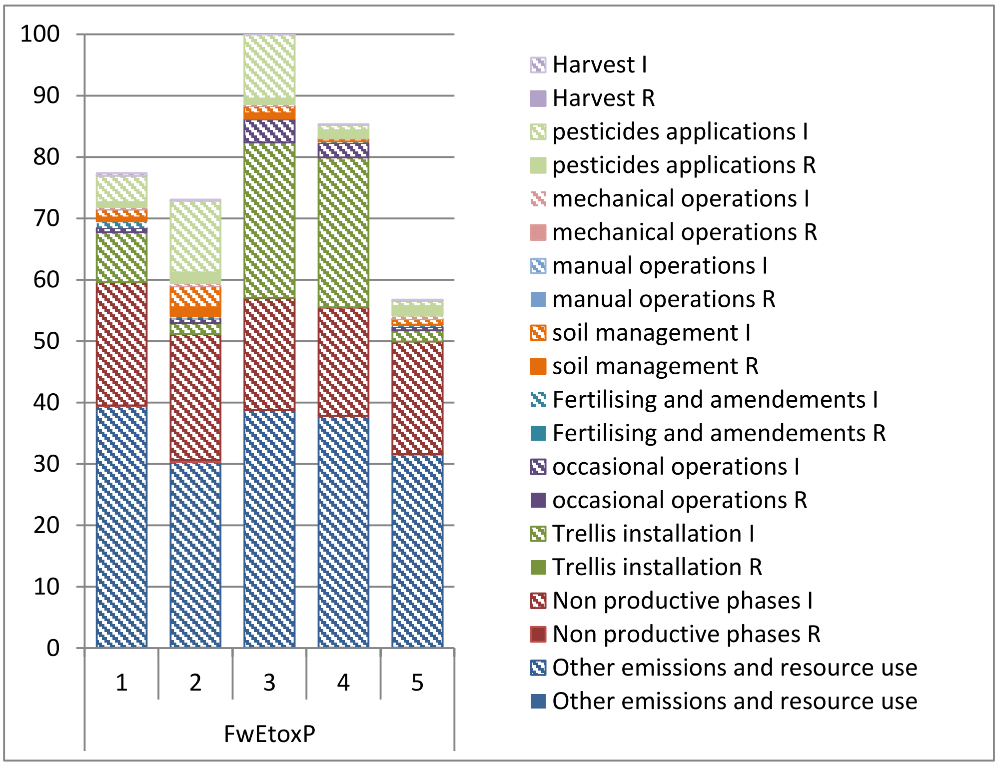

Figure F4: Contributions of TMR parts FwEtoxP impacts for the 5 TMRs showing the distinction between USETox results calculated with recommended and interim characterization factors.

# SYNTHESE

Ce chapitre avait pour objet de présenter et de mettre en œuvre le cadre méthodologique mis au point pour l'ACV des cinq itinéraires techniques viticoles (ITKv) sélectionnés. Notre objectif était d'observer dans quelle mesure l'ACV peut être adaptée au choix des techniques viticoles à l'échelle parcellaire. Il visait aussi à analyser la structure des impacts environnementaux d'une diversité régionale d'itinéraires techniques viticoles.

Les ITKv représentant les pratiques mises en œuvre en Moyenne Vallée de la Loire sur Chenin blanc pour la production de vins blancs secs AOC se montrent plus performants du point de vue environnemental que la plupart des cas décrits dans les ACV viticoles récemment publiées à l'échelle internationale.

La hiérarchie des performances environnementales des cinq ITKv étudiés ne correspond pas à la dichotomie conventionnel/biologique, mais rejoint assez bien les caractéristiques désignant les groupes que nous avons définis par la typologie régionale. Cette hiérarchie de performances varie selon les catégories d'impact (Tableau 22). L'ITKv 3 s'est montré le plus performant, le 1 et le 5 montrent des performances opposées selon les catégories d'impact et le 2 et le 4 offrent des performances moyennes.

*Tableau 22 : hiérarchie des performances environnementales des ITKv pour UF 1ha (du vert : meilleure performance, au rouge, moins bonne performance) pour les 9 catégories d'impact étudiées (les sigles sont explicités en dessous du tableau).*

| | GWP 100a[1] (kg $CO_2$ eq) | POFP[2] (vég) ( m2.ppm.h) | AP[3] (m²) | AEP-N[4] (kgN) | TEtoxP-100a[5] (kg 1,4-DB eq) | FwEtoxP[6] (CTUe) | Res[7] (kg) | LC [8] (m²a) | WU[9] ($m^{3)}$ |
|---|---|---|---|---|---|---|---|---|---|
| ITKv1* | 1212 | 13146 | 188 | 6,1 | 1,7 | 4500 | 0,9 | 12199 | 8,8 |
| ITKv2* | 1461 | 21561 | 277 | 6,9 | 0,3 | 4248 | 0,5 | 14927 | 7,2 |
| ITKv3* | 864 | 11930 | 120 | 4,7 | 0,8 | 5817 | 0,3 | 12659 | 3,5 |
| ITKv4* | 1290 | 20659 | 256 | 7,2 | 0,8 | 4962 | 0,5 | 13079 | 7,5 |
| ITKv5* | 1720 | 27915 | 337 | 7,2 | 0,6 | 3300 | 0,5 | 14394 | 7,0 |

Légende : − 🟩 🟩 🟩 🟨 🟨 🟧 🟧 🟥 +

*correspondant aux groupe :1-«traitement systématique de synthèse et travail manuel limité », 2 « usage modéré de traitements », 3 « traitements de synthèse et interventions minimaux », 4 « biologique modéré » et 5 « biologique intensif ».

[1]GWP 100a : potentiel de réchauffement climatique à 100 ans, [2]POFP (vég): potentiel de formation d'ozone photochimique, [3]AP: potentiel d'acidification, [4]AEP-N: potentiel d'eutrophisation lié à l'azote, [5]TEtoxP 100a: potentiel d'écotoxicité terrestre hors pesticides à 100 ans, [6]FwEtoxP: potentiel d'écotoxicité pour les organismes aquatiques d'eau douce, [7]Res: consommation de ressources abiotiques, [8]LC: utilisation d'espace, [9]WU: utilisation d'eau.

Les opérations techniques les plus impactantes sont le palissage (lié aux matériaux utilisés), la fertilisation, et l'usage des machines agricoles (par leur consommation de gasoil). La prise en compte des phases non productives dans l'ACV des ITK apparait donc essentielle.

Des pistes d'amélioration des performances environnementales sont possibles et leurs effets environnementaux peuvent être chiffrés par l'ACV comme le montre l'exemple du palissage traité dans ce chapitre.

Les résultats peuvent être généralisés aux ITKv similaires pour les catégories d'impact dont le calcul ne fait pas appel aux spécificités locales (sol climat) : GWP-100a, Res, WU, LC. Par contre, les autres catégories basées sur des calculs d'émissions directes demandent une adaptation à chaque site.

Pour une application au conseil de terrain, l'ACV, fournit des références utiles. Cependant, c'est une méthode complexe et longue à mettre en œuvre dont l'utilisation directe par les acteurs de terrain demande la mise en place d'outils simplifiés appuyés sur des bases de données secondaires et d'ICV de techniques viticoles.

Plusieurs éléments méthodologiques nécessitent d'être affinés ou développés : une meilleure prise en compte des cycles du carbone et de l'azote, l'établissement de modèles de calcul des émissions et des impacts adaptés aux pesticides inorganiques, le calcul de facteurs de caractérisation des matières actives utilisées en viticulture pour l'impact toxicité humaine, l'enrichissement de la base de données de consommation de gasoil par opération techniques, et de caractéristiques des fertilisants et amendements organiques disponible à ce jour, les impacts de la viticulture sur la qualité des sols et la biodiversité, l'exploration de l'amplitude des variations causées par le changement de millésime dans les conditions du Val de Loire, et enfin, la prise en compte de la fonction de production de raisins de qualité dans l'ACV.

## TRANSITION

Les deux chapitres suivants s'attachent à répondre aux deux derniers enjeux mentionnés ci-dessus : Quelle est l'amplitude de variation des résultats due à l'effet millésime en Val de Loire, et comment prendre en compte dans l'ACV la fonction principale de l'ITKv d'AOC qui est la production de raisins de qualité.

Le chapitre 4, présente donc les résultats d'une ACV comparative suivant le même cadre méthodologique que le chapitre 3 (avec toutefois un nombre réduit de catégories d'impact), sur l'ITKv 3 pour deux millésimes climatiquement contrastés et caractérisés: 2011 et 2013.

# CHAPITRE 5

# EFFET DU MILLESIME SUR LES PERFORMANCES ENVIRONNEMENTALES D'UN ITINERAIRE TECHNIQUE VITICOLE EVALUEES PAR ANALYSE DU CYCLE DE VIE (ACV)

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# MOTS CLES

Évaluation environnementale, ACV, itinéraire technique viticole, climat, raisin, vigne

# RESUME

La prise en compte de l'environnement dans le secteur viticole est de plus en plus prégnante. Elle amène les viticulteurs à réfléchir leurs itinéraires techniques viticoles (ITKv) sur des critères de performances environnementales. Nous analysons ici la variabilité des performances environnementales de l'ITKv d'une parcelle de Chenin Blanc, en viticulture raisonnée, produisant du vin blanc sec AOP (Appellation d'Origine Protégée) en moyenne vallée de la Loire (France) pour deux millésimes aux climats contrastés 2011 et 2013. Les impacts environnementaux de l'ensemble des opérations viticoles y compris plantation, mise à fruit et arrachage, sont évalués par la méthode d'analyse du cycle de vie (ACV). Le contraste climatique entre les deux millésimes 2011 et 2013, a été vérifié sur la base d'une typologie du climat de 32 années. Concernant les opérations viticoles, 2011, année précoce et 2013 fraiche et humide, se différencient principalement sur la fréquence des opérations de traitements phytosanitaires et les matières actives employées. Cela a un impact très important sur les résultats de l'ACV : 2013 est plus impactant sur toutes les catégories d'impact (sauf l'eutrophisation par l'Azote) notamment à cause des traitements phytosanitaires. Les consommations en gazole des machines, ici fortement liées à la fréquence des traitements phytosanitaires sont un fort générateur d'impacts et différencient les années. L'étude montre donc que, selon le millésime et sur une même parcelle, la variation des impacts environnementaux peut être importante dans plusieurs catégories d'impacts. Elle est induite par l'adaptation des itinéraires techniques viticoles aux conditions du millésime et aux conditions climatiques. Il est donc très important dans l'évaluation des impacts environnementaux des ITKv par ACV de tenir compte de cette variabilité.

# 1 INTRODUCTION

Actuellement, les pratiques viticoles évoluent vers la réduction des impacts environnementaux. Par exemple, la France, qui fait partie des trois plus gros producteurs de vins mondiaux avec l'Espagne et l'Italie (OIV 2013b) a mis en place des programmes de réduction de pesticides, avec l'objectif de réduire l'utilisation de pesticides de 50% entre 2008 et 2018 et de passer en agriculture biologique 20% de la SAU en 2020. Cette volonté de réduction des impacts rejoint les enjeux économiques de la filière que ce soit vis-à-vis de la réduction du coût des intrants ou pour s'adapter à la demande croissante des metteurs en marché, et de certains consommateurs, de. vins produits de manière respectueuse de l'environnement (Agence-Bio 2013; Symoneaux and Jourjon 2013).

Nous souhaitons donc répondre à cette problématique en fournissant aux professionnels des filières viticoles des éléments méthodologiques et techniques permettant le pilotage des Itinéraires Techniques viticoles (ITKv) au niveau des parcelles pour une meilleure performance environnementale.

Pour évaluer ces performances environnementales, il est possible d'utiliser des mesures directes dans le cas d'études simples ou de recourir à des méthodes d'évaluation indirectes basées sur des indicateurs (Bockstaller et al. 2009; Girardin et al. 2000). Dans un objectif de pilotage des ITKv, les mesures directes ne sont pas envisageables. Au vu de la complexité des ITKv et des phénomènes en jeu : ce sont donc des méthodes basées sur des indicateurs qui ont été retenues ici.

Différentes méthodes d'évaluation environnementale à l'échelle parcellaire existent (Bockstaller et al. 2009; Payraudeau and van der Werf 2005) mais l'Analyse de Cycle de Vie (ACV), méthode normalisée (ISO.14040 2006) est la seule permettant d'évaluer les différents impacts environnementaux potentiels sur l'ensemble du cycle de vie d'un produit. Cette méthode exprime les impacts relativement à un service rendu traduit par une Unité Fonctionnelle (UF), ce qui permet une comparaison objective de différents scénarii (Bellon-Maurel et al. 2012).

De nombreuses ACV sur différents systèmes agricoles ont été publiées depuis une vingtaine d'années. Celles qui concernent les cultures pérennes ont montré que les impacts étaient principalement dus aux carburants, à la consommation électrique, aux fertilisants, aux pesticides et à la consommation d'eau (Milà i Canals et al. 2006; Gallego et al. 2011; Beccali et al. 2010). Sur pommier, les travaux menés par Mouron et al. (2006) montrent, qu'une performance environnementale favorable est principalement basée sur l'utilisation efficace des technologies et sur le choix du meilleur moment pour les différentes opérations.

Toutefois, excepté deux études (Vázquez-Rowe et al. 2012b; Villanueva-Rey et al. 2014a), toutes les ACV viticoles publiées, comme la majorité des ACV de cultures pérennes, portent, sur une seule année de production. Or, il est important, pour les cultures pérennes, de prendre en compte les années non-productives mais également de tenir compte des variations annuelles en entrants et en sortants si on ne veut pas sous-estimer ou surestimer les impacts (Bessou et al. 2014; Vázquez-Rowe et al. 2012b). En effet, la gestion de l'ITK, dans un vignoble, est étroitement liée aux conditions climatiques et aux caractéristiques du sol. Ces paramètres jouent à la fois sur la croissance de la vigne et sur la maturité des raisins (Deloire and Hunter 2005; Jones et al. 2005; Duchêne et al. 2010).

Selon Van Leeuwen et al. (2004), les impacts du climat sont plus importants que ceux liés au sol et au cultivar pour la croissance de la vigne. Selon Ubalde et al. (2007), le climat conditionne jusqu'à 70% de la qualité du raisin. En Val de Loire par exemple, les grands millésimes sont liés à des conditions climatiques particulières à savoir une année plus chaude que la moyenne, avec un été peu pluvieux et un début d'automne sec et ensoleillé (Barbeau 2007).

Le climat est donc un facteur prépondérant pour la qualité des raisins et la croissance de la vigne. Dans le cadre d'un projet où nous cherchons à évaluer l'effet des pratiques sur les impacts environnementaux conjointement à la qualité des raisins, nous souhaitons observer dans quelle mesure le climat revêt, aussi, de l'importance dans le choix des pratiques et leurs impacts environnementaux associés.

La présente étude est consacrée à la comparaison des performances environnementales d'un ITKv sur deux millésimes distincts, évaluées par la méthode de l'ACV.

# 2 MATERIELS ET METHODES

## 2.1 CARACTERISATION DES MILLESIMES

Nous avons souhaité situer les millésimes envisagés au sein de la variabilité interannuelle d'une suite de 32 millésimes récents (millésime 1981 à millésime 2013). La station météorologique Météo-France de Beaucouzé (latitude : 47°28'42"N, longitude : 0°36'48"W, altitude : 50m), offrant les données les plus complètes pour la zone, et située à moins de 30km de la parcelle étudiée a été choisie.

Les 32 millésimes ont été classés par une classification ascendante hiérarchique (CAH) basée sur les résultats d'une Analyse en composantes principales (ACP) et consolidée par K-Means. (Husson et al. 2012).

La CAH consolidée par une analyse K-Means détermine les groupes de millésimes ressemblants. Cette fonction combine les facteurs principaux, la classification hiérarchique et le partitionnement pour mieux visualiser et mettre l'accent sur les similarités entre individus (Husson et al. 2012). Ce classement a été basé sur les températures, précipitations et ETP mensuelles d'avril à septembre, période de croissance de la vigne

Les analyses de données ont été réalisées grâce au logiciel R, package FactoMineR (Husson et al. 2012).

## 2.2 L'ACV

### 2.2.1 OBJECTIF

L'objectif de cette ACV est de comparer, pour une même parcelle, les impacts environnementaux des ITKv mis en œuvre en 2011 et 2013, deux millésimes contrastés d'un point de vue climatique. La parcelle de vigne étudiée produit du raisin de Chenin Blanc en moyenne vallée de la Loire (France) pour du vin Appellation d'origine contrôlée AOC Anjou blanc sec. Les ITKv étudiés sont en viticulture raisonnée sans toutefois répondre à un cahier des charges autre que celui de l'AOC Anjou blanc sec. Les vignes sont conduites en espalier, enherbées dans l'inter-rang, à 50% de la surface et plantées à 4884 pieds/ha.

### 2.2.2 CHAMP DE L'ETUDE

L'étude concerne la phase viticole de la production du vin. La mise en place du vignoble, les 3 années de mise à fruit et l'arrachage des vignes en fin de vie, ainsi que les opérations réalisées occasionnellement sont considérées, dans l'étude, après un amortissement sur la durée de vie de la vigne. Toutes les opérations concernant le travail du sol, la protection phytosanitaire, l'application de fertilisants et tous les travaux manuels et mécanisés sont prises en compte (Figure 28)

Le but est d'associer à chaque processus élémentaire (opération) des flux entrant et des flux sortant (ISO.14040 2006)

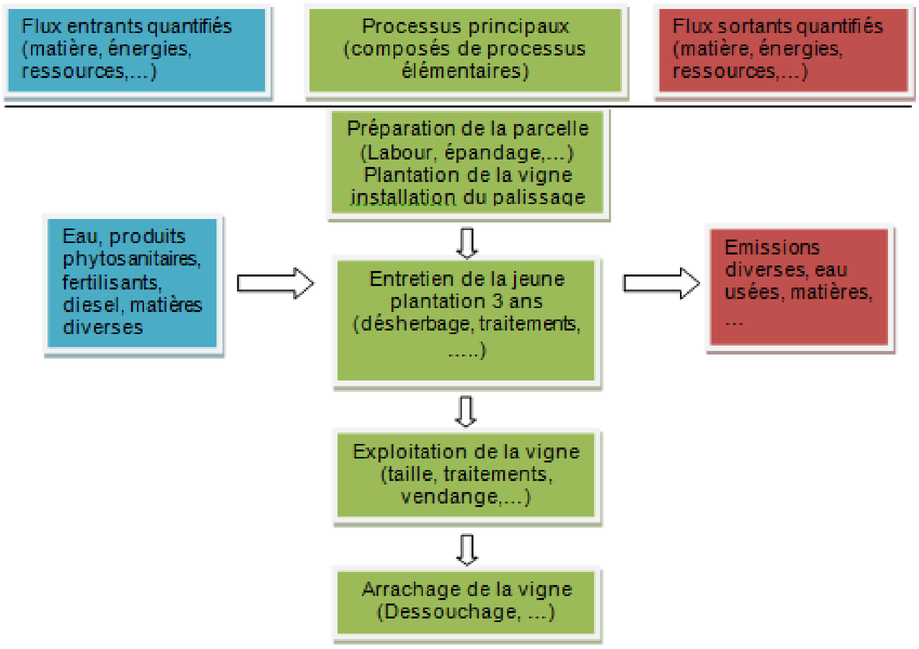

*Figure 28:Limites du système étudié représentées sous forme de processus et de flux*

### 2.2.3 POSTULATS DE DEPART

Le déplacement des ouvriers et des machines entre la parcelle et l'exploitation ou le siège de l'entrepreneur de travaux viticoles ont été inclus dans le système et comptabilisés sur une base standardisée. Le transport des intrants est évalué sur la base du poids de l'intrant et de la distance sur laquelle il a été transporté depuis son lieu de fabrication.

Le carbone n'a pas été pris en compte hormis pour les émissions liées à la combustion de carburant.

Les impacts de la construction et l'utilisation des bâtiments agricoles ont été inclus pour la surface (m²) requise pour le stockage des machines.

### 2.2.4 UNITE FONCTIONNELLE (UF)

L'ACV est une approche fonctionnelle. On étudie la fonction que remplit un produit, le service rendu. L'UF est la grandeur quantifiant la fonction du système, le service offert, sur la base de laquelle les scénarios sont comparés (Jolliet et al. 2010a). L'UF est l'unité à laquelle toutes les émissions et extractions seront rapportées.

La plupart des ACV du vin qui prennent en compte tout le cycle de vie utilisent comme UF un volume de vin produit (Rugani et al. 2013). D'autres études, plus rares (Villanueva-Rey et al. 2014a), prennent en compte le kg de raisin ou bien l'hectare de vigne (Renaud-Gentié et al. 2013). L'objectif de notre étude étant l'évaluation des ITKv pour le choix des pratiques viticoles, nous n'étudions que la phase de production de raisin. Les deux unités fonctionnelles retenues sont le kilogramme de raisin récolté et l'hectare de vigne. Le kg de raisin permet de chercher à minimiser les impacts d'une masse de produit (Renaud et al. 2010). Cette UF rend les résultats de l'ACV dépendants de la quantité de récolte, elle favorise les productions à rendements élevés. L'hectare de vigne permet de travailler à minimiser les impacts générés quand on cultive une surface donnée. Cette unité est indépendante de la quantité et de la qualité de la récolte, elle favorise les productions à faibles flux entrants.

### 2.2.5 COLLECTE DES DONNEES PRIMAIRES

L'inventaire des flux élémentaires est la description quantitative des flux de matière, d'énergie et de polluants qui traversent les limites du système (Jolliet et al. 2010a). Il regroupe donc les quantités de substances polluantes émises ainsi que les ressources extraites au cours du cycle de vie du produit ou du service analysé. L'inventaire de tous les flux élémentaires est rapporté à l'UF retenue.

Les données d'inventaire ont été recueillies auprès du viticulteur exploitant la parcelle par entretiens, puis saisis sur le logiciel Excel dans un fichier dédié (données primaires).

### 2.2.6 SOURCES DE DONNEES SECONDAIRES

Lorsque les données ne pouvaient pas être fournies par le viticulteur au vu de leur complexité et du niveau de détail attendu, nous avons fait appel à de nombreuses autres sources détaillées ci-après dans le Tableau 23, elles sont appelées les données secondaires.

*Tableau 23: données secondaires associées à leur référence*

| Type de données | Référence |
|---|---|
| Consommations de carburant par type d’opération | (Gaviglio 2010b) et entretiens avec l’auteur<br>Ecoinvent (Nemececk and Kägi 2007) |
| Durée de vie, facteur de réparation, espace de stockage, utilisation annuelle des machines | (Gazzarin and Vögeli 2011)et contacts avec l’auteur |
| Matières actives des produits phytosanitaires | Base de données e-phy (eMAAF and ONPV 2013) |
| Autres données relatives au matériel agricole, aux fournitures de palissage, les compositions de fertilisants | Fiches techniques des matériels, contact avec les fabricants, fournisseurs et constructeurs |

### 2.2.7 MODELES D’EMISSION DIRECTES

La quantification des émissions de polluants en agriculture nécessite de passer par des modèles de calcul, ces valeurs ne pouvant, dans la plupart des cas, pas être obtenues par des mesures.

Différents modèles de calcul ont donc été mis en œuvre pour évaluer les émissions directes au champ d’azote, de phosphore, de métaux lourds, de pesticides et les émissions liées à la combustion de carburant. Les rapports méthodologiques AGRIBALYSE® (Koch et Salou, 2013) et Ecoinvent (Nemecek and Kägi 2007) ont été utilisés comme références pour le choix d’une grande partie des modèles.

Le calcul des émissions d’ammoniac ($NH_3$) vers l’air est basé sur le modèle EMEP/EAA 2013 (Hutchings et al. 2013) niveau 2 . Pour les émissions de nitrates ($NO_3$-) vers les eaux souterraines, le modèle SQCB (Faist Emmenegger et al. 2011) adapté par AGRIBALYSE$^{®}$ (Koch and Salou 2013) a été retenu. Pour les émissions de protoxyde d’azote ($N_2O$) et autres oxydes d’azote ($NO_x$), c’est le modèle du GIEC (IPCC 2006) niveau 1 qui a été pris.

Les calculs d’érosion sont basés sur le modèle RUSLE (Foster 2005a) et les émissions de phosphore sur le modèle SALCA-P utilisé par Ecoinvent 2007 (Nemececk and Kägi 2007). Pour les métaux lourds, le modèle SALCA ETM (Freiermuth 2006) adapté à la France (Koch and Salou 2013) a été retenu. Les émissions de pesticides ont été estimées par le modèle Pest-LCI 2.0 (Dijkman et al. 2012) adapté à la viticulture par Renaud-Gentié et al. (2014b). Enfin, les émissions liées à la combustion des carburants ont été calculées selon le rapport ECOINVENT® (Nemececk and Kägi 2007).

### 2.2.8 CATEGORIES D’IMPACT

SALCA est une méthode d’évaluation du cycle de vie développée par Agroscope Reckenholz-Tänikon ART en Suisse (Nemececk and Kägi 2007). Elle sert à l’analyse et à l’optimisation des impacts environnementaux de la production agricole. SALCA est une compilation de différentes méthodes (Gaillard and Nemecek 2009) : ECOINVENT® (2007), IPPC (2007), EDIP 2003, CML 2001 et de catégories dites d’inventaire, c’est-à-dire ne faisant pas appel à un facteur de caractérisation. Nous avons par ailleurs utilisé USETox$^{TM}$ (Rosenbaum et al. 2008). Parmi les catégories d’impacts disponibles dans SALCA et USETox$^{TM}$, nous avons choisi celles qui sont listées dans le Tableau 24.

Ces catégories d’impact sont celles utilisées fréquemment dans les études ACV sur le vin (Rugani et al. 2013; Neto et al. 2013; Fusi et al. 2014b; Vázquez-Rowe et al. 2012b). Toutefois les auteurs n’utilisent pas toujours la même méthode de caractérisation.

La toxicité humaine, bien que représentant un enjeu important pour la viticulture, n’a pas été évaluée ici par manque de facteurs de caractérisation concernant les matières actives employées. Concernant l’ecotoxicité aquatique, le facteur de caractérisation du Folpel anormalement élevé dans Usetox a été recalculé pour nos travaux à partir de données mises à jour (Renaud-Gentié et al. , en révision)

Le logiciel utilisé pour les calculs d’ACV est Simapro 8 (Pré Consultants).

*Tableau 24: définition des catégories d’impacts utilisées*

| Catégories d'impact | Abréviation<br>( unité) | Référence | Définition |
|---|---|---|---|
| Réchauffement climatique à 100 ans | GWP 100a (kg $CO_2$ eq) | IPCC 2007 | Réchauffement climatique dû aux émissions de gaz à effet de serre ($CO_2$, $CH_4$, $N_2O$,…) |
| Formation d’ozone troposphérique (effet sur la végétation) | POFP (vég) ( m2.ppm.h) | EDIP 2003 | Formation par des précurseurs de type $NO_x$, COVNM et Hox, d'ozone dans la troposphère, polluant de l'air, nocif pour l'homme, la faune et la flore. |
| Acidification | AP (m²) | EDIP 2003 | formée par certains gaz ($SO_2$, $NO_x$, HCl…) en présence d'humidité; elle se traduit par des pluies acides et la perte de fertilité des sols. |
| Eutrophisation aquatique en azote | AEP N (kgN) | EDIP 2003 | Enrichissement des eaux de surface en matière organique riche en N |
| Consommation de ressources | Res (kg) | EDIP 2003 | Consommation de ressources non renouvelables (minerais, gaz naturel, pétrole, charbon…) |
| Ecotoxicité aquatique eau douce | FwEtoxP (CTUe) | USETox$^{TM}$ | Effets nocifs de composés chimiques sur les espèces vivant en eau douce |

# 3 RESULTATS

## 3.1 CLASSIFICATION DES MILLESIMES

A l’issue de la CAH, consolidée par K Means, donnant 4 classes de climat, les 2 millésimes étudiés 2011 et 2013 appartiennent à deux classes distinctes (Figure 29) et sont donc contrastés entre eux.

Le millésime 2013 est caractérisé sur la période de croissance de la vigne par des températures fraîches voire froides qui ont occasionné une vendange tardive. De plus, lors de ce millésime, il y a eu une forte pression en parasites et maladies. Par contre, le millésime 2011 est caractérisé par un climat à températures chaudes qui a entraîné une vendange précoce, avec une faible pression cryptogamique (DGAI-SDQPV 2011, 2013)

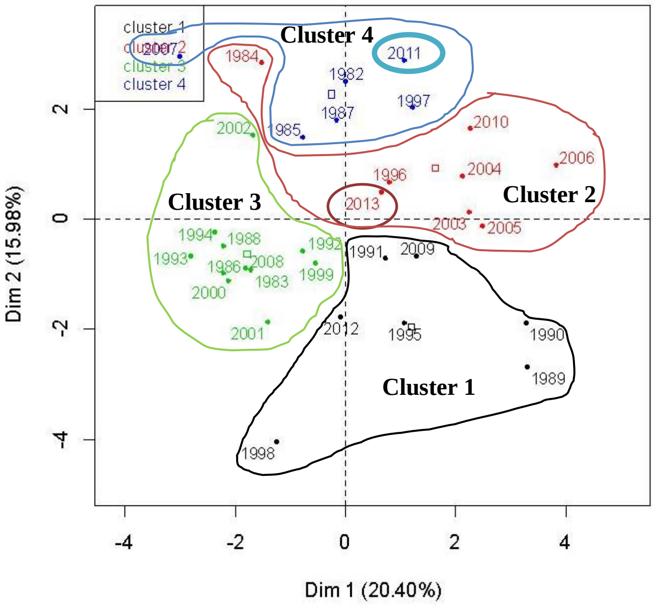

*Figure 29 : Classification K-Means représentée sur la carte ACP, dimensions 1 et 2, le carré de couleur représente le barycentre du groupe. Les deux millésimes étudiés sont entourés*

## 3.2 INTERPRETATION DES RESULTATS D’ACV

### 3.2.1 MILLESIME 2011 AVEC UNITE FONCTIONNELLE 1 HECTARE.

La Figure 30 montre les contributions des différentes parties de l’ITKv aux impacts exprimés par hectare de vigne.

Les 5 groupes de pratiques les plus contributifs sur la majorité des impacts sont l’installation du palissage, les opérations mécaniques, les émissions indépendantes des intrants, la fertilisation et amendements et les traitements phytosanitaires.

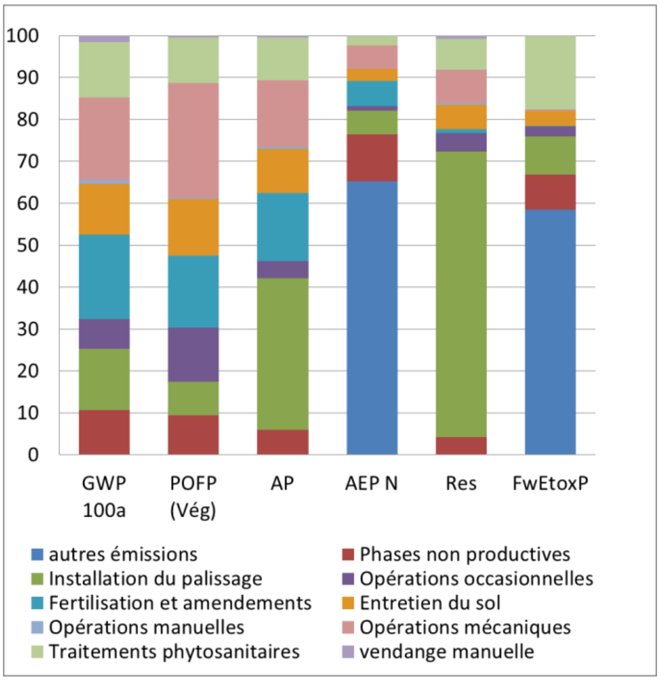

*Figure 30: ACV de l'ITKv3, 2011, analyse des contributions UF 1 ha, méthode: SALCA V1.02 et USETox/ Caractérisation / Exclusion des émissions à long terme*

Il est intéressant de noter que, pour toutes les catégories d'impacts, les opérations manuelles et les vendanges (ici manuelles) ont peu d'impacts (<4% des différentes catégories d'impacts). En effet, les travaux réalisés manuellement n'engendrent que les impacts liés au transport du personnel à la parcelle et le cas échéant à l'utilisation d'un petit outillage.

Il faut souligner à l'opposé, la place non négligeable des phases non productives sur les 6 catégories d'impacts. Il est donc important de les prendre en compte, ce qui vient confirmer l'étude de Bessou et al. (2014).

Il est à noter enfin que pour le réchauffement climatique et la formation d'ozone troposphérique, on retrouve des proportions de contributions aux impacts très proches entre les processus.

Le Tableau 25 recense les principales causes des impacts pour les millésimes 2011 et 2013

Concernant **le réchauffement climatique (GWP-100a)**, « fertilisation et amendements » (20,1%) et les opérations mécaniques (19,7%) sont les principales sources d'impact notamment à cause de la consommation de gasoil et la fabrication du compost (Tableau 25). La contribution de la majorité des autres opérations a pour origine également la fabrication et la consommation de gasoil.

La fabrication du compost (Tableau 25) provenant du groupement fertilisation et amendements (16,2%) est à l'origine d'une grande part de la **formation d'ozone troposphérique (POFP).** La contribution de la majorité des autres opérations a, comme dans la catégorie d'impacts GWP-100a, pour origine la fabrication et la consommation de gasoil.

*Tableau 25 : Récapitulatif des contributions sources selon les catégories d'impact lors du millésime 2011 (en italique) et* **2013** *(en gras)*

| Catégorie d'impact | Impact supérieur ou égal à 40% | | Impact supérieur ou égal à 20% | | Impact supérieur ou égal à 10% | |
|---|---|---|---|---|---|---|
| | cause d'impact | % d'attribution | cause d'impact | % d'attribution | cause d'impact | % d'attribution |
| Réchauffement climatique | consommation de diesel | (*45%*, **51**%) | - | - | fabrication du compost | (*18%*,**13**%) |
| Formation d'ozone troposphérique | - | - | - | - | fabrication du compost | *(16%,* **12**%) |
| Acidification | - | - | Zinc | (*31%*,**24**%) | fabrication du compost<br>consommation de diesel | (*16%*,**12**%)<br>(*10%*, 12%) |
| Eutrophisation aquatique en azote | Autres émissions de 2011, 2013 | (*65%*, **40**%) | - | - | - | - |
| Ressources | Zinc | (*56%*, **48**%) | Ferronickel | (*20%*, **26**%) | - | - |
| Ecotoxicologie aquatique | Autres émissions | (*58,5%*, **59***%)* | Fabrication fongicides | (-,**17**%) | fabrication Mancozèbe<br>Agent de protection du bois des piquets | (*15%*, -)<br>(*10%*, -) |

L'**acidification (AP)** est principalement causée par l'installation du palissage (36,2%) notamment à cause de l'utilisation du revêtement en zinc des fils et des amarres d'acier galvanisés (Tableau 25). La fertilisation et amendements prend une place importante également à 15,6%. Tous les autres processus et notamment les opérations mécaniques (16%) sont impactants à cause de la fabrication et de la consommation de gasoil (Tableau 25).

La très forte part (65,2%) des « autres émissions » dans la catégorie d'impact **eutrophisation aquatique liée à l'azote (AEP-N)** a pour origine la lixiviation de nitrates présents dans le sol qui est très importante par rapport à celle des nitrates contenus dans les intrants.

Pour la **consommation de ressources (Res),** l'installation du palissage est le principal processus impactant. Les ressources principalement impactantes sont le zinc entrant dans la fabrication des fils d'acier galvanisés et l'emploi de ferronickel lors de la fabrication de machines et de tracteurs (Tableau 25).

Concernant **l'écotoxicité (FwEtoxP)**, les « autres émissions » génèrent la plus grande partie de l'impact (58,5%). Les 17,5% dus aux traitements phytosanitaires viennent majoritairement de la fabrication du Mancozèbe (Tableau 25). L'agent de protection du bois de palissage compte également pour une part importante avec 9,9% des impacts.

### 3.2.2 MILLESIME 2013 AVEC UNITE FONCTIONNELLE 1 HECTARE.

Les résultats du millésime 2013 à l'hectare (Figure 31) montrent une répartition des contributions assez proche de celle observée en 2011 pour certains impacts (GWP-100a, POFP (vég), AP et Res). Cette répartition est, par contre, très différente pour AEP-N et FwEtoxP.

Avec l'installation du palissage, les opérations mécaniques, l'entretien du sol, la fertilisation et amendements, les émissions indépendantes des intrants, les traitements phytosanitaires sont les processus offrant les plus grandes contributions.

En 2013, le climat a amené le vigneron à réaliser nombre important de traitements : 7 traitements contre 4 traitements lors du millésime 2011, ce qui a accru leur contribution à toutes les catégories d'impact (de 14 à 60% d'augmentation).

Les « autres émissions » représentent la grande majorité des impacts concernant **l'eutrophisation aquatique en azote** et l'**écotoxicité aquatique.** Pour cette dernière**,** la deuxième source de contribution sont les traitements phytosanitaires principalement à cause de la fabrication des fongicides.

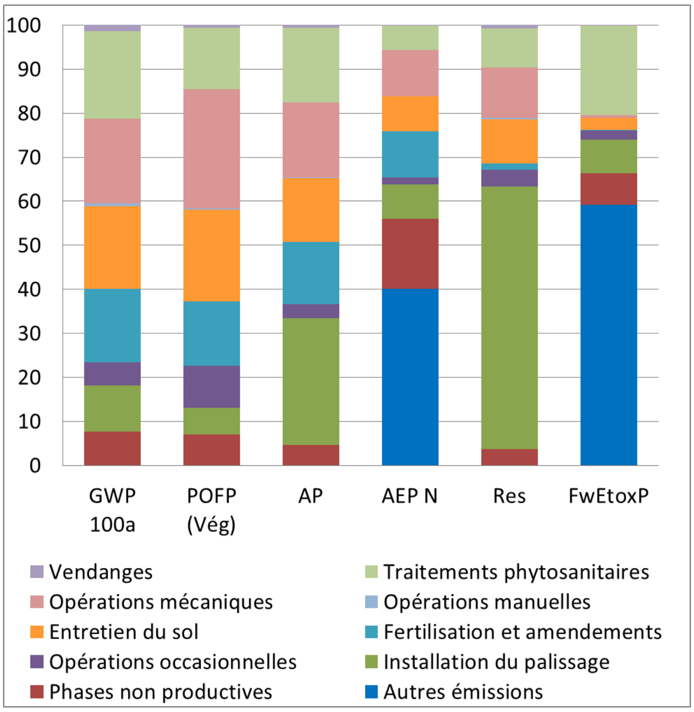

Figure 31: Analyse de contributions, UF 1 ha ITKv3, 2013,
*Méthode : SALCA V1.02 et USETox/ Caractérisation / Exclusion des émissions à long terme*

Comme en 2011, pour les mêmes raisons, et pour tous les impacts, les opérations manuelles et les vendanges (manuelles) ont peu d'impact (<2%).

Pour **le réchauffement climatique (GWP-100a)**, les traitements phytosanitaires (21,2%), les opérations mécaniques (20,6%) et l'entretien du sol (20,2%) sont impactants à cause de la fabrication et de la consommation de gasoil (Tableau 25). La fertilisation et amendements

(17,5%) est également une des principales sources d’impact notamment à cause de la fabrication du compost (Tableau 25).

Pour la **formation d’ozone troposphérique (végétation) (POFP),** les opérations mécaniques (28%), l’entretien du sol (21,5%) sont les principaux contributeurs. Le compost de marc de raisin prend une part importante également (Tableau 25).

L’**acidification potentielle (AP)** est comme en 2011 principalement représentée par l’installation du palissage (28,7%) et la fertilisation et les amendements (14,3%) dus au compost. Tous les autres processus et notamment les traitements phytosanitaires (17%), les opérations mécaniques (17%), et l’entretien du sol (14%) sont impactants à cause de la fabrication et la consommation de gasoil (Tableau 25).

La forte part (40%) des émissions indépendantes des intrants dans la catégorie d’impact potentiel d’**eutrophisation aquatique liée à l’azote (AEP-N)** est liée au lessivage des nitrates présents dans le sol. Elle est bien inférieure, cependant, à celle de 2011 du fait d’un régime de pluies moins favorable au lessivage tel qu’estimé par le modèle SQCB. Les phases non productives occupent une part importante également avec 15,9%.

Pour la **consommation de ressources (Res),** l’installation du palissage (59,7%), est comme en 2011 et pour les mêmes raisons, le principal contributeur.

Concernant **l’écotoxicité aquatique potentielle (FwEtoxP)**, les « autres émissions » causent le principal de l’impact (59,2%) et la fabrication et le transport des traitements phytosanitaires le deuxième (16,8%) (Tableau 25).

## 3.3 COMPARAISON DES IMPACTS DES ITKV 2011 ET 2013

### 3.3.1 COMPARAISON 2011/2013 AVEC UNITE FONCTIONNELLE 1 HECTARE

Sur 5 des 6 catégories d’impacts étudiées, le millésime 2013 présente plus d’impact que 2011 (Figure 32) avec une augmentation de 12% à 28%.

Le millésime 2011 a, par contre, plus d’impact que celui de 2013 pour l’eutrophisation aquatique liée à l’azote, car une grande partie de cet impact est liée aux « autres émissions », en particulier les nitrates qui ont été plus fortement lessivés en 2011 qu’en 2013 du fait des conditions climatiques.

Comme on a pu le voir précédemment, le millésime 2013, du fait de son climat, a occasionné une plus forte pression en ravageurs et maladies et la vigne a donc nécessité plus de traitements phytosanitaires (75% de plus qu’en 2011), mais aussi un rognage et deux désherbages chimiques supplémentaires, ce qui est la cause principale des impacts supérieurs en 2013 par rapport à 2011.

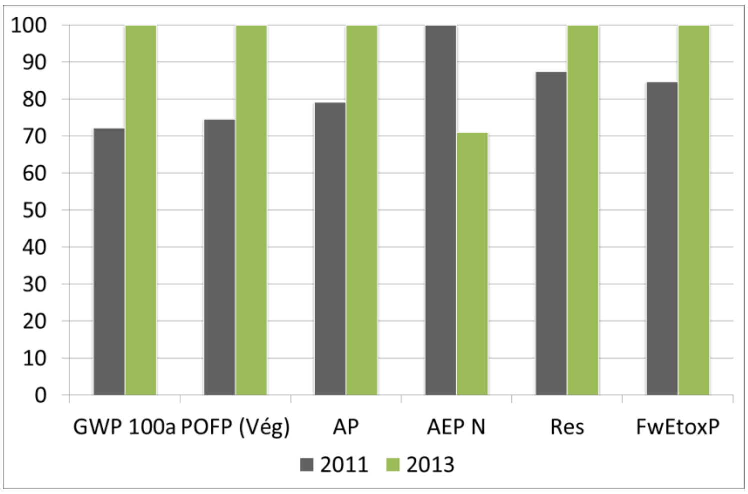

*Figure 32 : comparaison des impacts du millésime 2011 et 2013 ramenés à l'UF de 1 ha*

Le potentiel de réchauffement climatique montre une différence de près de 30% entre les deux millésimes.

### 3.3.2 COMPARAISON 2011/2013 AVEC UNE UNITE FONCTIONNELLE 1 KG

La parcelle lors du millésime 2011 a eu un rendement de 7500 kg/ha et de 9750 kg/ha en 2013. De ce fait, lorsque l'on ramène les impacts au kilogramme de raisins, les écarts s'amenuisent pour tous les impacts excepté l'eutrophisation (AEP-N) (Figure 33).

En effet, les impacts sont alors comparables entre les deux années pour GWP 100a, POFP (Vég), AP et FwEtoxP. L'écart des impacts de l'eutrophisation aquatique en azote entre 2011 et 2013 est accentué par rapport à l'UF à l'hectare pour atteindre presque 50%.

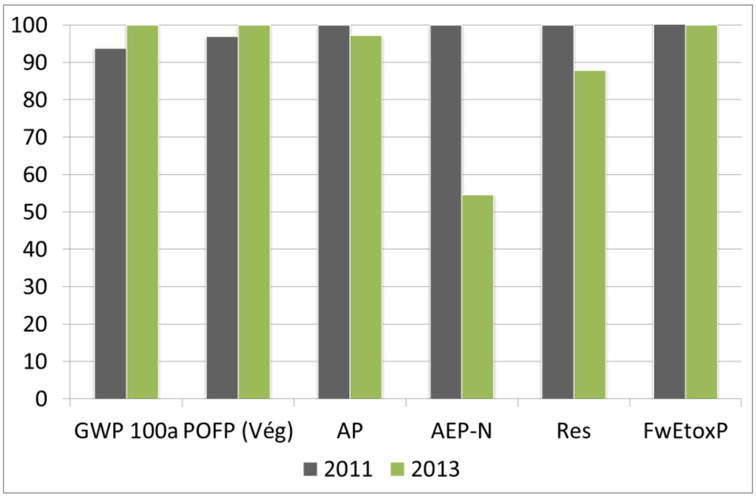

*Figure 33: comparaison des impacts des millésimes 2011 et 2013 pour l'UF 1 kg de raisin.*

Ainsi, sur les 6 catégories d'impacts, 2 montrent un impact supérieur (légèrement) de l'ITK en 2013 par rapport à l'ITK en 2011 contre 5 dans le cas de l'UF à l'hectare.

# 4 DISCUSSION

En ce qui concerne plus spécifiquement les ACV en viticulture, la plupart des études s'intéressent aux pratiques de la parcelle à la mise en bouteille et donc prennent en compte viticulture et vinification. Aranda et al. (2005) montrent que l'utilisation de fertilisants et de pesticides a le plus d'impacts environnementaux lors de la phase de culture de la vigne, cette phase représentant 32 % des impacts totaux d'une bouteille de vin. Dans le cas étudié par Point et al.(2012), c'est l'utilisation de fertilisants à base d'azote qui est le plus grand contributeur aux impacts (principalement pour l'eutrophisation et l'acidification). Vázquez-Rowe et al.(2012b) identifient également le processus de consommation de diesel comme étant important dans la plupart des catégories d'impact.

De manière générale, les impacts les plus recensés pour la production de raisins sont le réchauffement climatique, l'écotoxicité aquatique, l'acidification, l'eutrophisation, l'utilisation d'espace, et l'oxydation photochimique (Point et al. 2012; Petti et al. 2006a; Vázquez-Rowe et al. 2012b).

Dans notre étude, les consommations en carburant sont les sources d'impact les plus récurrentes. En découle la place prépondérante des opérations mécaniques (applications d'intrants et entretien mécanisé du vignoble), par rapport aux opérations manuelles (taille, vendanges, accolage, ébourgeonnage, etc…), ces-dernières ayant peu d'impacts.

Le compost de marc de raisin utilisé comme fertilisant est également une source d'impacts récurrente en 2011 sur trois catégories d'impacts GWP-100a, POFP et AP entre 10 et 20% d'impacts. Concernant l'eutrophisation en N, le fertilisant représenté par le compost ne domine pas l'impact car le pool d'azote du sol est pris en compte dans le calcul du lessivage et représente la part majeure de l'azote lessivé (autres émissions), il est toutefois à noter que ce pool provient des partiques de fertilisation des années antérieures (prises en compte de manière forfaitaire ici).

Concernant les pesticides, dans la très grande majorité des cas, ce ne sont pas les substances actives en elles-mêmes qui sont les plus impactantes mais leur application qui utilise du gasoil, voire leur fabrication. Cependant, certaines matières actives présentent un potentiel d'écotoxicité plus fort que les autres. Vazquez-Rowe et al.(2012b) et Villanueva-Rey et al. (2014), seuls auteurs ayant quantifié l'impact écotoxicité aquatique selon la même méthode que celle appliquée dans la présente étude (avec toutefois une version antérieure du modèle PestLCI), identifient le Folpel comme une des matières actives les plus impactantes avec le cuivre et la Therbutylazine. Ces deux dernières substances n'ont pas été utilisées dans les deux ITK étudiés ici (la Therbutylazine est interdite en France) Concernant le Folpel, nous obtenons un résultat similaire à ces auteurs quand nous utilisons les facteurs de caractérisation présents originellement dans Usetox, toutefois, avec les facteurs recalculés, le Folpel ne domine plus les impacts.

Comme on a pu le voir précédemment, ces résultats rejoignent en partie les conclusions des ACV publiées dans le domaine viticole à savoir que le gasoil, les fertilisants et les pesticides sont les plus grandes sources d'impacts (Aranda et al. 2005; Gazulla et al. 2010; Point et al.

2012; Vázquez-Rowe et al. 2012b; Benedetto 2013; Fusi et al. 2014a; Villanueva-Rey et al. 2014a).

La consommation de gasoil est citée par Vázquez-Rowe et al.(2012b) et Benedetto (2013) comme étant importante dans la plupart des catégories d'impact. Villanueva-Rey et al. (2014) montrent que la production et la consommation de diesel représentent 59% en moyenne des contributions. Nous avons des valeurs comparables à 45% en 2011 et 51% en 2013 pour le réchauffement climatique.

La place de la fabrication du compost rejoint en partie les conclusions de Vázquez-Rowe et al. (2012b) qui indiquent que la fabrication et le transport du compost comptent pour plus de 50% des impacts dans les catégories d'impacts suivantes : réchauffement climatique, l'acidification, la consommation de l'espace et la formation d'oxydant photochimique. Aranda et al. (2005) indiquent que les fertilisants et les pesticides représentent 39% des impacts totaux. Pour Point (Point et al. 2012), l'application d'intrants azotés est le principal contributeur dont 16% pour le GWP. Dans notre étude, il représente 18% (GWP-100a) et 16% (POFP et AP) d'impacts pour 2011 et 13% (GWP-100a), 12% (POFP et AP) d'impacts pour 2013.

Les « autres émissions », ne pouvant être attribuées directement à aucune opération technique, représentent 65% (AEP-N) et 59% (FwEtoxP) pour 2011 et 40% (AEP-N) et 62% (FwEtoxP) pour 2013. De nombreux auteurs font part d'un fort impact des fertilisants (50% et plus pour AEP-N) dans ces catégories d'impact mais ne font pas mention de la prise en compte ou non des émissions non attribuables à des processus identifiés (autres émissions) (Vázquez-Rowe et al. 2012b; Villanueva-Rey et al. 2014a), ces autres émissions ont-elles été exclues du système étudié ou comptabilisées dans celles dues aux fertilisants ? Nous n'avons pu le vérifier.

A l'encontre d'autres études, Vázquez-Rowe et al. (2012b) mentionnent que la production de pesticides a globalement de faibles impacts (<10%). Fusi et al. (2014b) posent l'hypothèse que les émissions de pesticides sont négligeables. C'est ce qu'on retrouve dans notre étude. L'existence de substances actives largement utilisées à fort potentiel écotoxique comme par exemple l'Aclonifen ou le Cymoxanil (non utilisées ici) justifie toutefois la prise en compte des émissions de pesticides dans l'évaluation des ITKv.

Les variations de rendement entre millésimes (23% entre 2011 et 2013) jouent un rôle important dans les variations d'impacts rapportés au kg de raisin, elles peuvent ainsi accroître ou réduire la variabilité constatée à l'hectare. L'utilisation conjointe des deux UF est donc nécessaire : les variations d'impact liées aux pratiques et aux variations d'émissions dues au climat sont traduites dans les impacts calculés à l'ha ; et dans l'UF 1kg de raisin s'ajoute la variabilité due au niveau de rendement.

Les consommations de gasoil jouent un rôle essentiel dans les impacts constatés ici. Toutefois, si les ordres de grandeurs et les comparaisons entre les millésimes peuvent être considérés comme corrects, le détail des valeurs absolues doit être pris avec précaution du fait de la difficulté à disposer d'une source pertinente, fiable et unique, pour l'évaluation des consommations de carburant pour les différents types d'opérations. Nous avons en effet dû faire appel à des sources différentes. La source de données prioritaire est l'étude des performances énergétiques des matériels viticoles (Gaviglio 2010b) et des entretiens avec l'auteur de ce rapport, M. Gaviglio. Cependant, pour les opérations dont la consommation de gasoil n'a pas été étudiée dans l'étude IFV de 2009, nous avons du utiliser le rapport méthodologique de la base de données d'inventaire du cycle de vie Ecoinvent (Nemececk and Kägi 2007) qui concerne la matériel agricole (grandes cultures) moyennant des adaptations.

# 5 CONCLUSION

Cette étude a évalué, par l'Analyse du Cycle de Vie (ACV), les performances environnementales d'un itinéraire technique viticole déployé sur une même parcelle lors deux millésimes aux conditions climatiques contrastées durant la phase de croissance de la vigne (2011 et 2013).

Les résultats montrent que ce contraste climatique, qui a occasionné un nombre différent d'interventions mécanisées et d'applications de pesticides, s'est répercuté sur la majorité des impacts environnementaux étudiés. L'année 2011, plus sèche et précoce présente ainsi des impacts à l'hectare inférieurs de 12% à 28% à ceux de 2013. Le principal facteur responsable de ces écarts est le nombre de traitements phytosanitaires qui est 75% plus important en 2013 qu'en 2011.

En 2013, les traitements phytosanitaires sont plus présents et ont un impact important pour la quasi-totalité des catégories d'impacts.

Pour les deux millésimes, on retrouve les mêmes principaux contributeurs aux impacts en proportions approchantes entre les deux années pour quatre des impacts étudiés (GWP100a, POP (veg), acidification et ressources (all)). L'eutrophisation due à l'azote est, ici, principalement liée aux émissions non directement dépendantes des intrants et dépend majoritairement du régime des précipitations de l'année entière. Ses variations dépendent donc peu de l'itinéraire technique mis en œuvre.

Les principaux groupes de pratiques responsables des impacts sont l'installation du palissage (même une fois amortie sur la durée de vie de la vigne), les opérations mécaniques, les « autres émissions », les « fertilisation et amendements » et les traitements phytosanitaires**.** Pour le millésime 2013 s'ajoute également l'entretien du sol

Au sein de ces groupes, ce sont la consommation de gasoil, la fabrication du compost, les émissions directes non directement dépendantes des intrants, l'utilisation de zinc et de ferronickel pour la fabrication des machines et du palissage, et l'utilisation de produits phytosanitaires (fabrication principalement) qui ont causé les impacts les plus importants.

Le calcul des impacts au kilogramme de raisin récolté réduit les différences d'impacts entre les deux millésimes car le rendement de 2011 est inférieur de 25% à celui de 2013.

Ceci ne concerne pas l'eutrophisation aquatique due à l'azote qui est le seul impact où le millésime 2013 est moins impactant que le millésime 2011, mais l'écart n'est pas lié aux pratiques mais directement au climat.

Ces travaux confirment, en accord avec des études sur d'autres cultures pérennes, qu'il est essentiel de prendre en compte la variabilité des pratiques entre millésimes dans les ACV viticoles. Ceci est notamment capital lorsque l'on souhaite décider d'évolution des pratiques pour l'amélioration des performances environnementales sur la base des résultats d'ACV, ou pour l'établissement de références en vue de réaliser un affichage environnemental par exemple.

Il sera intéressant d'élargir cette comparaison à d'autres types d'itinéraires techniques viticoles, et de comparer les proportions de cette variation à celles de variations entre systèmes contrastés.

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## SYNTHESE

L'objectif de ce quatrième chapitre consistait à observer l'effet d'un changement de millésime sur les résultats de l'ACV d'un itinéraire technique viticole (ITKv) dans les conditions de la moyenne Vallée de la Loire. L'ITKv 3, représentant le groupe 3 « traitements de synthèse et interventions minimaux » a été observé sur deux millésimes contrastés du point de vue du climat et de la pression parasitaire.

Les différences de fréquences de passages de machines et dans les quantités et la nature des matières actives utilisées pour les traitements anti-fongiques ont occasionné des différences d'impact dans la majorité des catégories. L'année 2011, plus sèche et précoce présente des impacts inférieurs à l'hectare de 12% à 28% à ceux de 2013.

La différence observée entre les millésimes pour le potentiel de réchauffement climatique ne dépend pas directement des conditions climatiques mais des pratiques mises en oeuvre par le vigneron pour s'y adapter, par contre la différence observée sur le potentiel d'eutrophisation de l'azote dépend très peu des pratiques.

Etant donné ce potentiel de variation interannuelle des impacts, il apparait donc essentiel de prendre en compte la variabilité des pratiques entre millésimes dans les ACV viticoles, que l'on souhaite décider d'évolution des pratiques pour l'amélioration des performances environnementales ou établir des références.

## TRANSITION

Dans le cinquième et dernier chapitre, nous allons proposer une première approche de prise en compte de la qualité des raisins dans le calcul d'eco-efficience des ITKv de production de raisins de qualité. Ceci sera fait à travers deux unités fonctionnelles : un degré de correspondance à l'objectif qualitatif, et 1kg de raisin affecté du degré de correspondance à l'objectif qualitatif. L'utilisation d'une matrice d'éco-efficience est aussi proposée.

# CHAPITRE 6

# ECO-EFFICIENCY OF VINEYARD TECHNICAL MANAGEMENT ROUTES PART II: INCLUDING GRAPE QUALITY IN LIFE CYCLE ASSESSMENT

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# KEY WORDS

Environment, practices, winegrowers, LCA, grape, impacts, improvement, Protected Denomination of Origin, vine, quality

# 1 INTRODUCTION

Since the past decade, the wine sector faces growing social, institutional and economic pressure towards decreasing its environmental impacts. For example, in France, following the national environmental roundtable in 2007, the government’s policy on ecological and sustainable development includes the target of a 50% reduction in the use of pesticides between 2008 and 2018 (MAP 2008). Viticulture is a major pesticide user (in France 20% of pesticides consumption in mass on 3% of the agricultural area (Aubertot et al. 2005a)). Moreover, a new requirement for environmental product declaration, also relevant to wine, could be imposed in the coming years at French or European scale. Recent studies have shown that environmental aspects of wine production are important to a part of wine consumers (Remaud et al. 2010; Vecchio 2013; Symoneaux and Jourjon 2013), but that they are not ready to trade off the organoleptic quality of wine with environmental considerations (Lockshin and Corsi 2012).

In a context of Protected Designation of Origin (PDO) wines embodying the local and traditional technical know-how; there is a guarantee of origin, but not of environmental quality. However, French wine consumers attach implicitly an environmental friendliness dimension to PDOs (Jourjon and Symoneaux 2014). Besides societal and institutional demands of environment preservation, PDO wine producers must take into account the growing environmental requirements of key international markets. The viticulture phase of wine production is one of the highest contributors to wine environmental impacts (Neto et al. 2012; Fusi et al. 2014a) together with glass bottle manufacturing. The evolution of the wine industry‘s viticultural practices is, hence, crucial to reduce environmental impacts. It is therefore necessary to assist the wine industry in addressing this issue through the evolution of its viticultural practices to reduce environmental impacts in the specific context of PDO, where a part of the techniques are fixed by sets of rules.

However, this environmental impact reduction must not be done at the expense of the quality of the wine. Even if wine quality is multidimensional, and must satisfy a complex set of consumers’ expectations (Hérault-Fournier and Prigent-Simonin 2005), its organoleptic aspect remains the basic requirement, especially for PDO wines production. Environmental improvement of vineyard management should, for this reason, take into account the effects of vineyard management on grape quality, evaluation methods and future decision tools will have to combine environmental and quality dimensions.

Among the environmental assessment methods for agriculture (Bockstaller et al. 2009), Life Cycle Assessment (LCA) is the most holistic, as it is multi-criteria and multi-impacts and accounts for the whole life cycle of the product. LCA was originally developped from the industrial production systems, but is now frequently applied to agriculture (van der Werf et al.

2013). It was more recently applied to perennials including viticulture (Gazulla et al. 2010; Vázquez-Rowe et al. 2012b; Bessou et al. 2013; Cerutti et al. 2014; Fusi et al. 2014a; Villanueva-Rey et al. 2014b).

It opens interesting and new fields of improvement for vineyard Technical Management Routes (TMRs) regarding environmental burdens (Renaud-Gentié et al. to be submitted; Bellon-Maurel et al. 2014). This method calculates potential environmental impacts of the whole life cycle of a product (from raw materials extraction to product's end of life) related to a Functional Unit (FU) which corresponds to the product's main function. (Heller et al. 2013).

To our knowledge, none of the published wine sector LCA studies account for quality criteria in spite of the key importance of grape quality in wine final quality (Bravdo 2001b; Guidetti et al. 2010) and in spite of the importance of wine quality for wine consumers (Lockshin and Corsi 2012).

Quality, in its broad sense, is scarcely considered in food and crop LCA studies. In a milk production LCA, Müller-Lindenlauf et al. (2010) included milk quality, predicted from cows diet composition, as an additional impact besides classical LCA environmental impacts. Nevertheless, the most frequent option for quality accounting in food LCAs is to consider that quality is one of the main functions of the product. Hence quality is included in the FU. Let's give some examples (Charles et al. 2006) used a FU including a single quality criterion for wheat: "1 equivalent ton grain with 13% protein", implying a correction on yield and protein content based on well-known yield-protein content relations. Multi-criteria nutritional value of the various foods composing diets have more recently been considered in LCAs of diets through single indices resulting from the aggregation of the nutritional values of each foodstuff related to daily consumer needs (Kägi et al. 2012; Saarinen 2012; Heller et al. 2013). Some authors even included qualifying and disqualifying nutrients in the score (Van Kernebeek et al. 2014). Inaba and Ozawa (2008) proposed, for LCAs of meals, a comprehensive food-value index constructed on the same principle but involving taste, nutrient balance and health function of the dishes of a meal including weighting factors determined by consumer survey. Nevertheless, as pointed out by (van der Werf et al. 2014), inclusion of quality consideration in FUs remains a major challenge for the LCA Food community, especially for certified productions that favor quality over volume, as is typically the case for PDO wine production.

Like food nutritional quality, wine-grape quality is multi criteria (Geraudie et al. 2010). Its assessment usually permits the choice of the optimal harvest date, steering grapes to different types of wines, wine making management, and payment of grape providers. The most usual quality indicators for white grapes are sugar and soluble acids content, and also polyphenol content for red cultivars. However, more and more practitioners complement this maturity assessment of grapes with on-field sensory analysis (Winter et al. 2004; Le Moigne et al. 2008a; Le Moigne et al. 2008b; Siret et al. 2013; Patron et al. 2014) (Olarte Mantilla et al. 2012) especially for aromas, color or texture consideration obtaining thus a more integrative assessment. The sanitary state of the berries is also an important quality determinant. The presence of Botrytis bunch rot is especially problematic for white wine elaboration (Hill et al. 2014).

In the context of PDO wine production, wine organoleptic quality, and hence grape quality, is a key target of vineyard management. The improvement of Technical Management Routes[8] (TMR) by introducing more environmentally friendly techniques needs to take into account this quality dimension in addition to the yield function usually considered in wine and grape LCAs. The concept of eco-efficiency appeared to us well adapted to express this objective. This concept was originally developed to relate economic value and environmental impact of a good (Huppes and Ishikawa 2005); we used it taken as the ratio between, as numerator, emissions and resource use and as denominator, the service they provide, expressed by the FU (Kicherer et al. 2007).

Four objectives were pursued in order to design and implement eco-efficiency of viticulture related to the quality of the grapes: i) define LCA process and details with respect to crop- and site- specificities (this process was detailed in part I of this paper (Renaud et al., to be submitted), ii) design a synthetic index of grape quality, and a (quality x yield) index, iii) test the sensitivity of the index to a change of quality target; iv) implement a quality-related eco-efficiency calculation on five real and contrasted TMRs, v) test a quality-based eco-efficiency matrix.

The aim of the paper at hand is to present and discuss two proposals of inclusion of quality into the eco-efficiency assessment of quality grape production in order to support the choice and design of vineyard TMRs preserving the environment while maintaining the targeted quality.

This paper presents i) the material and methods: the general framework of the study, the LCA framework briefly, the grape quality index formula construction, and the grape quality measurements methods; ii) The results: grape quality assessment of the five TMRs and the resulting two quality-related FU calculations, a sensitivity analysis of the quality index to the quality target, eco-efficiency results for mass- and quality-based FUs compared and discussed, and the eco-efficiency matrix that combines environment and quality iii) a wider discussion on methods and perspectives and iv) a conclusion.

# 2 MATERIAL AND METHODS

## 2.1 GENERAL FRAMEWORK

The process of eco-efficiency assessment including grape quality is described in Figure 34: the dotted lines represent the steps treated in the part I paper (Renaud-Gentié et al. to be submitted) and the solid lines the steps described in the paper at hand (part II). The TMR is at the center of the assessment process, with soil and climatic conditions and the vine and cover-

---

[8] Technical Management Routes (TMRs): logical chain of practices managed by a farmer in a field (Sébillotte 1974)

crop shapes (density and geometry of the canopies). The research work was conducted in Middle Loire Valley PDOs Anjou Blanc, Saumur Blanc and Savennières, on five real TMRs (TMR1 to 5) that represent respectively the five main TMR types (Clusters 1 to 5) defined by the Typ-iti method (Renaud-Gentié et al, 2014) for Chenin Blanc cultivated for dry white PDO wines in the Middle Loire Valley: Cluster 1 characterized by “Systematic chemical use and limited handwork”, Cluster 2 “Moderate chemical use”, Cluster 3 “Minimum synthetic treatments and interventions”, Cluster 4 “organic moderate” and Cluster 5 “organic intensive”. Environmental assessment results were presented in part I of the paper, and environmental impacts were expressed for two FUs: 1 ha of productive vineyard cultivated during one year and 1 kg of grapes. On the right side of the figure, quality assessment was based on the comparison between measured grape quality at harvest, and a grape quality target.

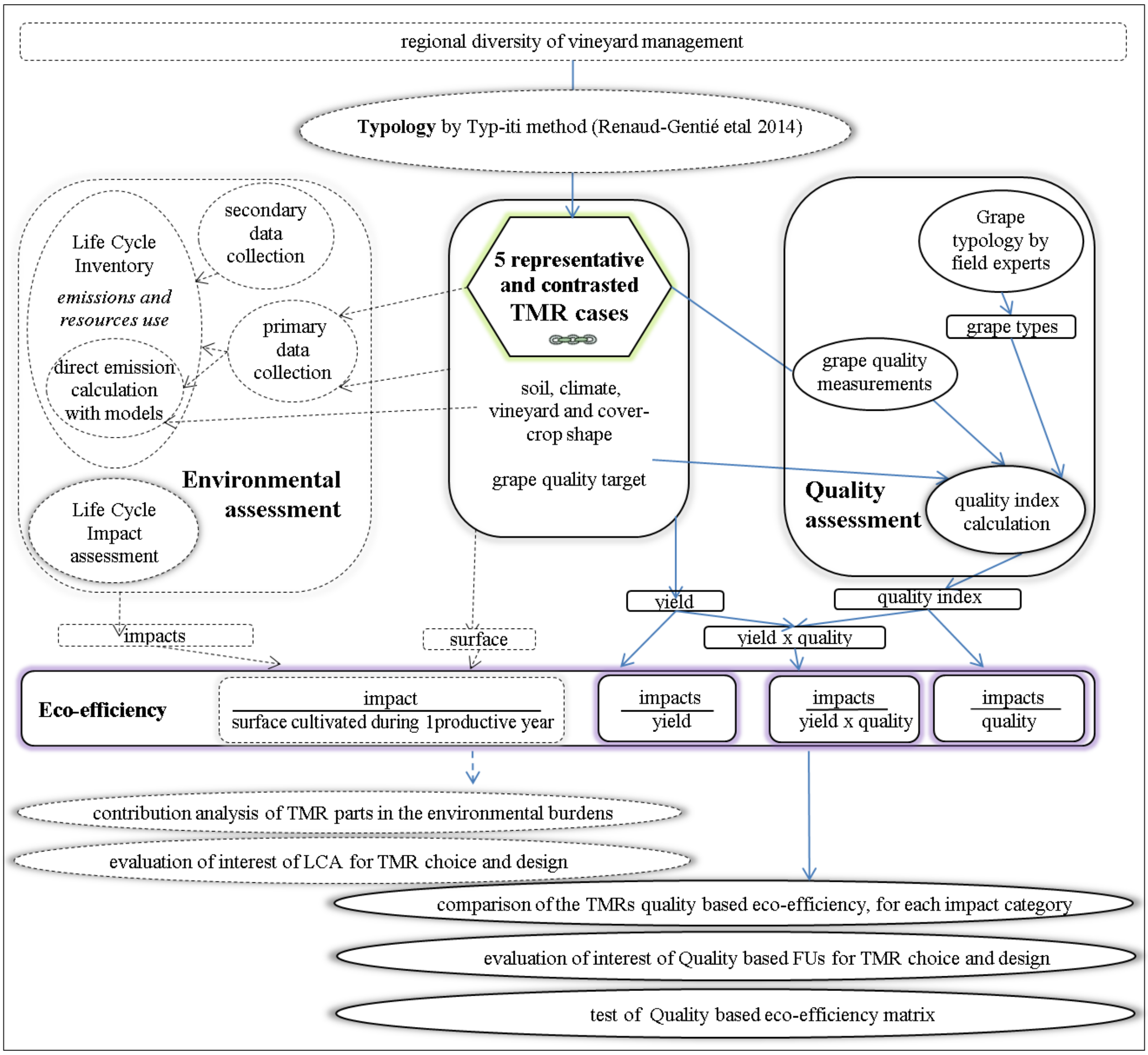

*Figure 34: General framework of the Eco-efficiency of vineyard technical management routes study*
Part I, environmental assessment (paper 1) in dotted lines and part II, inclusion of quality in the eco-efficiency assessment (paper 2) in solid lines

This target was expressed in terms of grape types the characteristics of which were defined by expert consensus, and a combined quality indicator (QI) was calculated. It was used as FU, as well as QI x yield. giving eco-efficiency results in four different functional units.

## 2.2 LIFE CYCLE ASSESSMENT

LCA was performed on the five contrasted TMRs. The life cycle inventory and LCA methodological framework are described in part I (Renaud-Gentié et al. to be submitted).

The choice of FU can considerably influence LCA results, this is important, especially in the case of scenario comparisons. For example in Alaphilippe et al. (2013), environmental performances of organic orchards expressed per ha are better than those of conventional and integrated orchards, but they are worse per kg apple. This difference was not found in the present study (part I (Renaud-Gentié et al. to be submitted)) because the differences in yield between the TMRs augmented most of the differences found per ha, in the conditions of 2011. For example, TMR3 had the lowest values per ha for most of the impacts, and it also had the highest yield, thus TMR3 had even less impacts per 1 kg grapes than per “1 ha vineyard cultivated during one productive year” compared to the other TMRs.

A standard bottle of 750 ml has been the most common FU used in previously published LCAs of the wine industry (Gazulla et al. 2010; Neto et al. 2012; Vázquez-Rowe et al. 2012b; Fusi et al. 2014a). The present study focuses on grape production because, as a major contributor to environmental impacts of the wine, grape production is a primary place of possible environmental performance improvements through sound evolution of practices. Grape production’s main goal in PDO areas is to satisfy the winemaker’s requirements of a sufficient quantity of quality grapes for making quality and typical wine. However, viticulture is multifunctional (Galletto and Bianchin 2009) and the system combines at least four main functions that are here translated into four FUs presented in increasing order of interest in the context of PDO wines production;

i) maintaining aesthetic landscape value (Joliet 2003; Briffaud 2011), which is particularly important in PDO areas where vine, as a perennial crop, occupies land for several decades, and is historically attached to the landscape appearance. Surface FU accounts for the goal of minimizing the impacts while cultivating a given area (Nemecek 2001; Mouron et al., 2006,). Finally, this FU is useful to communicate results to winegrowers who reason all their technical operations, especially input quantities, per ha;

ii) providing a given quantity of raw material for wine production. Mass FU (1 kg of grapes) reflects a part of the goal of economic sustainability of the wine estate (a bottle of dry white Anjou Blanc PDO wine in average Middle Loire Valley conditions requires approx. 1.125 kg grapes). However, (Huglin 1998) mentions the very frequent negative correlation between yield on the one hand and grape total soluble solids concentration and maturity potential on the other hand, primarily in cool climates. The choice of a single mass FU would, hence, harm the best-quality productions and low-input ones like some organic systems where more risks are taken on yield in order to reduce inputs per ha;

iii) providing a given quality of raw material for making a given type of quality wine. Quality FU = quality index. This requires the design of a combined quality index accounting for the multi-criteria nature of grape quality related to the type of wine targeted. A proposal of index calculation is made in section 2.3;

iv) providing a quantity of grapes with a quality fulfilling the requirements for the targeted wine making: quality-corrected mass FU (1 kg x quality index). According to Heller et al. (2013), this type of FU is well suited to comparing agricultural production methods.

Eco-efficiency results of the five TMRs expressed per 1 ha and 1 kg were detailed in Part I (ref), thus in this paper we will compare the results of the two new quality-based FUs and 1 kg grapes FU.

## 2.3 GRAPE QUALITY INDEX

### 2.3.1 CONCEPT OF THE INDEX

The quality of a product can be defined as the “degree to which a set of inherent characteristics fulfills requirement” (ISO 2005a). This can be translated into a quality index close to some of the nutritional profiling indexes used in LCAs of meals and diets (Heller et al. 2013). “Target” seemed to us more suited to grape quality than “requirement”:

*Equation 1*

$$Quality\ index\ = weight_1 \left|\frac{criterion1}{target\ for\ criterion1}\right| + weight_2 \left|\frac{criterion2}{target\ for\ criterion2}\right| + \cdots$$

Still, grape quality criteria do not always have a linear relation with the target, but various types of relations, depending on the nature of the criterion. For example, for a given type of grapes, sugar content can be optimal (according to a specific desired wine quality) between 200 and 220 g/l; under 200 g, the grapes are not accepted and over 220 g/l they can be accepted with a lower satisfaction until 250g/l, and above 250g/l be no longer accepted.

We propose to solve the problem by a set of logical rules of inference per criterion considering several levels ***e*** of correspondence to the target: ***e***=100%: perfect correspondence, e=0%: out of the target, not acceptable. If different secondary targets are acceptable, intermediate levels are added: e%: lower but acceptable degree of correspondence to the target, as many levels of correspondence as needed must be added.

For a given targeted grape type, for an assessed grape g, described by n criteria, with i=1 to n, the degree of correspondence $C_{ig}$ of the grape g to the quality target, for criterion $c_i$ is calculated according to the following formula:

*Équation 1*

$$\mathrm{C_{ig}} = \begin{cases} 100 & if\ c_{ig} \in \mathrm{A}_i \\ e_i & if\ c_{ig} \in \mathrm{B}_i \\ 0 & if\ c_{ig} \in \mathrm{D}_i \end{cases}$$

with $A_i \cap B_i = \emptyset$ and $B_i \cap D_i = \emptyset$ and $A_i \cap D_i = \emptyset$
and with $A_i U B_i U D$ include all $c_{ig}$
and with :
$C_{ig}$= degree of correspondence to the target of criterion i for grape g.
$c_{ig}$= value of criterion i for grape g
$A_i$ = set of values of criterion i corresponding to the target quality
$B_i$= set of values of criterion i corresponding to a secondary target quality, considered as acceptable
$e_i$= value of degree of correspondence to the initial target of a secondary target quality for criterion i
$D_i$=set of values of criterion i not acceptable
The limits of sets $A_i$, $B_i$, and $D_i$ and $e_i$ are fixed considering that the secondary target is $(1-e_i)$% less satisfying that the primary target.

The quality index $Q_g$ is the global degree of correspondence to the quality requirements for the grape g, it is the result of the weighted average of the degrees of correspondence to target of each criterion:

*Équation 2* :

$$Q_g = \frac{(\sum_{n}^{i=1} w_i C_{ig})}{\sum_{n}^{i=1} w_i}$$

With :

$Q_g$ = Quality index of grape g
$w_i$ = weight given to criterion i

## 2.3.2 APPLYING THE QUALITY INDEX TO GRAPE, DEFINITION OF REQUIREMENTS AND CRITERIA WITH EXPERTS

Applying the previous definition of the quality index to wine grapes implies to define $A_i$, $B_i$, $e_i$, and $D_i$. i.e. primary and secondary target grape types and their inherent characteristics. These characteristics are the criteria describing the grape and the gap between the primary target and the secondary targets (grape types permitting to make an acceptable quality wine, but not matching the initial target).

Wine grapes are destined to be used as raw material for winemaking, thus the requirements are defined by winemakers. Expert knowledge elicitation was used in several studies for environmental evaluation or soil quality assessment for the generation of criteria and thresholds (Tobias and Tietje 2007). In the same objective, we worked with nine middle Loire Valley expert practitioners frequently dealing with Chenin Blanc grapes linked to different PDO dry wines types: three extension officers or cooperative technicians, three oenologists-winemakers of big size cellars, three winegrowers-winemakers of individual cellars. The aim was to obtain a list of the main quality assessment criteria and quality requirements for Chenin Blanc grapes for dry PDO Middle Loire Valley wines. We established with them the list of existing grape types suited for this type of wine and their characteristics. The first step was an individual face to face interview resulting in a list of the primary grape quality criteria and a list of existing types of Chenin Blanc grapes in their working context. The second step was a consensus session between the experts, where they had to find an agreement about the primary grape quality criteria, the main grape types and their characteristics. Berries sugar content, aromas maturity (green – fresh fruit – cooked fruit), sanitary state and color of the berries (green to golden) were identified as the key parameters which differentiate the types of grapes of Chenin Blanc for Middle Loire Valley PDO dry wines.

### 2.3.3 APPLYING THE QUALITY INDEX TO GRAPE – DEFINITION OF RULES OF INFERENCE

From the survey based on experts mentioned previously, emerged the list of grape types. Table 26 describes the types of Chenin Blanc grapes for dry white wines with the values of the criteria corresponding to the quantitative (for sugar and rot) or qualitative (for berry color and aroma) limits of Ai for each grape type.

*Table 26: Chenin Blanc grape types suitable for dry still wine in Middle Loire Valley PDO context and their characteristics according to expert consensus*

| berry color | dominating aroma | sugar content in potential % alcohol | % of rotted berries | type | type code |
|---|---|---|---|---|---|
| Green or yellow | fresh fruits | 11>>13 | < 10% * | fresh dry wine | FD |
| Golden | ripe fruits | 13>>14.5 | < 10% * | ageing dry wine, ripe aromas | ADR |
| Golden | cooked fruits, jam, honey | 14.5>>16 | < 10% * | ageing dry wine, over-ripe aromas | ADOR |
| Golden | cooked fruits, jam, honey | 14>>16 | noble rot | ageing dry wine, noble rot aromas | ADN |

*except if it is grey mold is evolving into noble rot, then rot is accepted

We translated the qualitative values given by the experts for color and aromas into quantitative ones relatively to the existing scales that our sensory analysis panel was trained to use. Berry color is assessed by comparison to a visual scale from green to brown (Figure 35).

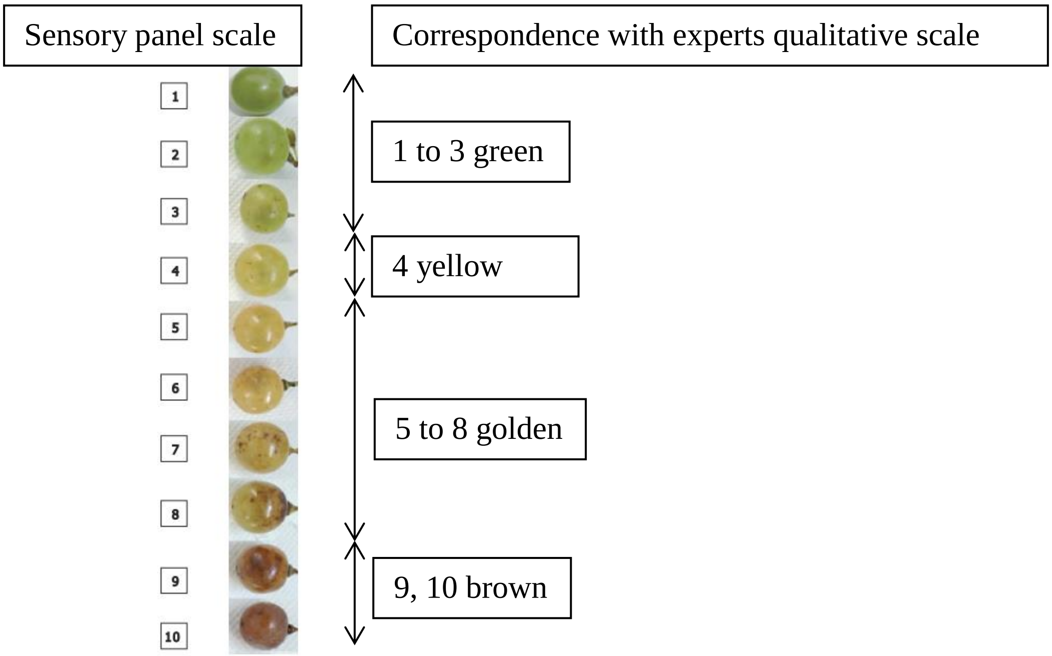

*Figure 35: color scale for Chenin blanc berries sensory analysis, source (UMT-Vinitera et al. 2013) and correspondence established with experts qualitative scale*

The experts called the grape types according to the wine that they are the most suitable to produce.

Correspondence between grape typology and single criteria assessment was done through the inference rules presented in Table 27.

*Table 27: rules of inference determined for grape type ADR as primary target and types FD and ADOR as secondary targets with both e=50%*

| **criterion number** | measured parameter (scale or unit) | **$A_i$** | e % | **$B_i$** | e % | **$D_i$** | e % |
|---|---|---|---|---|---|---|---|
| **$c_1$** | berry color ( /10) | $4<c_1<9$ | 100 | $2<c_1<4$ | 50 | $2>c_1$ or $c_1>9$ | 0 |
| **$c_2$** | dominant aroma | $c_2$ = ripe fruits | 100 | $c_2$=fresh fruits or $c_2$=cooked fruits, jam, honey | 50 | $c_2$ = vegetal, or earthy/moldy | 0 |
| **$c_3$** | sugar content (potential %alc.) | $3\leq c_3\leq 14{,}5$ | 100 | $11<c_3<13$ or $14{,}5<c_3<16$ | 50 | $11>c_3$ or $c_3>16$ | 0 |
| **$c_4$** | rot (%) | $c_4<10$ | 100 | | | $c_4>10$ | 0 |

$A_i$ = set of values of criterion i corresponding to the target quality, $B_i$= set of values of criterion i corresponding to a secondary target quality, considered as acceptable, $e_i$= value of degree of correspondence to the initial target quality, $D_i$=set of values of criterion i not acceptable

These rules were determined for the type of wine targeted by the growers in this study: type ADR, dry quality wine for ageing with ripe aromas as main target and type FD, fresh dry quality wine, and type ADOR, ageing dry wine, over-ripe aromas, as acceptable alternative targets (Table 27).

### 2.3.4 SENSITIVITY ANALYSIS OF QUALITY INDEX

In order to test the sensitivity of the index to the change of target, a test was done considering the primary target was "grape type FD", with two secondary targets "grape type ADR" with a degree of correspondence to target e=50% and "grape type ADOR" with e= 25%.

*Table 28: rules of inference determined for grape type FD as primary target and types ADR and ADOR as secondary targets with respectively e=50% and e=25%*

| **criterion number** | parameter (scale or unit) | **$A_i$** | e % | **$B_i$** | e % | **B'i** | e % | **$D_i$** | e % |
|---|---|---|---|---|---|---|---|---|---|
| **$c_1$** | Color( /10) | $c_1 \leq 4$ | 100 | $4<c_1<9$ | 50 | $c_1>9$ | 25 | $2>c_1$ or $c_1>9$ | 0 |
| **$c_2$** | dominant aroma | $c_2$=fresh fruits | 100 | $c_2$ = ripe fruits | 50 | $c_2$=r cooked fruits, jam, honey | 25 | $c_2$ = vegetal, or<br>$c_2$ =default | 0 |
| **$c_3$** | sugar content (potential %alc.) | $11<c_3<13$ | 100 | $13 \leq c_3 \leq 14{,}5$ | 50 | $14{,}5<c_3<16$ | 25 | $11>c_3$ or $c_3>16$ | 0 |
| **$c_4$** | rot (%) | $c_4<10$ | 100 | | | | | $c_4>10$ | 0 |

## 2.4 QUALITY CRITERIA MEASUREMENTS

Based on this criteria list, data collection was done on grapes from the 5 selected plots at harvest time in October 2011.

All sampling and measurements were done, for each plot, on the same consecutive 40 vines, chosen in a homogeneous and representative part of the plots.

Harvest date being of great importance in grape composition (Cadot 2010), the grape samples were harvested with the same number of days after veraison (+/- 2 days): 40 days was chosen on the basis of the experience of the previous year and the harvest dates forecasted by the winegrowers.

### 2.4.1 SUGAR CONTENT

Sugar content (Brix) was measured by refractometry (Refracto 30PX, Mettler Toledo, the apparatus corrects the effect of temperature on the refraction index) on the juice of a representative sample of 200 berries taken on the 40 marked vines, the measure was repeated once, and converted in potential alcohol by volume using the conversion table of the Compendium of International Methods of Analysis –OIV(CIMA-OIV 2012) and the mean was taken as result.

### 2.4.2 SANITARY STATE OF THE BERRIES AT HARVEST

Sanitary state of the berries was visually assessed on each bunch of the 40 vines, determining frequency (percentage of grapes diseased) and intensity of disease (percentage of diseased berries on each bunch).

### 2.4.3 SENSORY ANALYSIS OF BERRIES AND MUST

An extra 300 berries representative sample was used for berries sensory analysis, on 27 attributes and from which the berry color assessment results were extracted. Musts sensory analysis results were used to determine aromas. The musts were obtained from the pressing of approx. 5 kg of grapes harvested on the same 40 vines at the same date, and were frozen at -20°C in 60 ml containers, after addition of 0.02 $gl^{-1}$ $SO_2$ and 1 day debourbage at 4°C, to permit an assessment on a same day. They were defrosted at 4°C 24 h before assessment and were put at ambient temperature 4 h before presenting them to the panel. The berries and musts were assessed on a 0 to 10 continuous scale for each parameter, by an expert panel of 11 judges for the berries and 13 judges for the musts. The panel was trained (10 training sessions of 1 h in the previous 6 months on white grape berries sensory analysis plus 3 x 1 h sessions specific to Chenin blanc must sensory analysis), and assessed as discriminating, homogeneous and repeatable. All assessments were repeated once. The attributes selected as corresponding to experts grape typology criteria - berry color, must vegetal aroma, white fruits (for fresh fruits) and prune (for cooked fruits) aromas- were found discriminating in the analysis of variance with P-values lower than 0.01.

## 2.5 APPLICATION OF QUALITY FUNCTIONAL UNITS TO LCA RESULTS

The environmental impact for each impact category relatively to the Quality index, $Q_g$ is obtained by dividing the “per ha” LCA results by $Q_g$ (%). The mass x quality ($MQ_g$) FU derives from the calculation of a mass-quality index, $MQ_g$, by multiplication of the annual grape yield by $Q_g$ (%). The environmental impact results, in this case, are obtained by dividing the “per ha” LCA results by $MQ_g$ obtaining results per $MQ_g$ FU.

## 2.6 QUALITY-ENVIRONMENT TRADE-OFFS

We propose to build an eco-efficiency matrix to visualize quality-environment trade-offs, and observe which TMR gives the best compromise between grape quality and environment, i.e. the best eco-efficiency (Figure 36). The quality index is used independently from the FU. The FU is here 1kg of grapes. $Q_g$ is related to impacts per kg. This kind of representation is close to the one proposed by Huppes and Ishikawa (2009) to represent the process of eco-innovation.

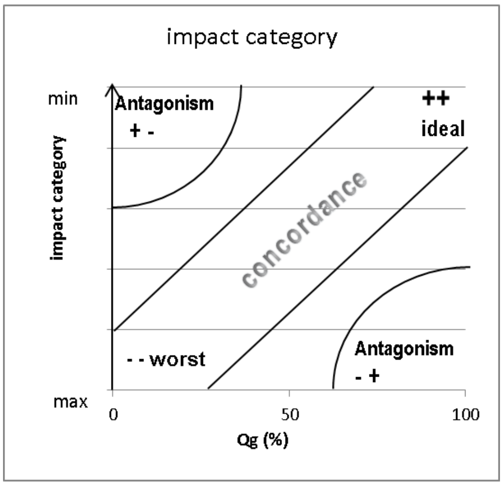

*Figure 36: model of Eco-efficiency matrix designed for relating environmental impact and grape quality of the TMRs*

The most eco-efficient TMRs will be situated in the "ideal" zone. The totally uninteresting solutions would be found in the "worst" zone, the "antagonism" zones concern the TMRs that would satisfy only one objective: either environmental performance or grape quality.

# 3 RESULTS

## 3.1 QUALITY ASSESSMENT

### 3.1.1 QUALITY MEASUREMENTS RESULTS AND QUALITY INDEX CALCULATION

The results of the sensory analysis concerning aromas showed no differences at Fishers Least Significant Difference (LSD) test, for any of the attributes. They were analyzed to extract the dominating aroma (Table 29), in accordance with expert description of grape types, for inclusion in the quality index determination table (Table 30). The five TMRs yielded grapes dominated by fresh fruit aroma.

*Table 29: Results of assessment of aromas on grape juice and determination of dominating aroma. In italic, the non-discriminating attributes from ANOVA (product + judges + product x judges) for P-value <5% , in bold, the higher values.*

| Aroma family | Juice aroma (scale) | TMR1 | TMR2 | TMR3 | TMR4 | TMR5 |
|---|---|---|---|---|---|---|
| vegetal aromas | « green » aroma (/10) | 2.37 | 3.11 | 2.36 | 2.72 | 2.52 |
| | cut grass aroma (/10) | 2.72 | 3.70 | 2.63 | 3.33 | 3.11 |
| fresh fruit aromas | white fruit aromas (/10) | **3.76** | **3.81** | **3.64** | **3.68** | **3.21** |
| | citrus aromas(/10) | 1.59 | 1.78 | 1.58 | 1.33 | 1.49 |
| ripe fruit aromas | *yellow fruit aromas( /10)* | *0.40* | *0.59* | *0.43* | *0.45* | *0.82* |
| | *exotic fruit aromas (/10)* | *0.94* | *0.49* | *0.43* | *0.71* | *0.43* |
| cooked fruit aromas | prune, honey, jam (/10) | 0.41 | 0.4 | 0.44 | 0.43 | 0.55 |
| Other aroma | *flower aroma (/10)* | *0.55* | *0.47* | *0.55* | *0.33* | *0.43* |
| defaults aromas | *Σ( fungi, mold, earth) (/30)* | *0.24* | *0.04* | *0.03* | *0.04* | *0.21* |
| Dominating Aroma | | Fresh fruit | Fresh fruit | Fresh fruit | Fresh fruit | Fresh fruit |

Table 30 reports the construction of Quality index ($Q_g$) based on the results of measured quality criteria and the dominant aroma. Two levels of $Q_g$ appear for the five TMRs (62.5 and 75). The difference is related to a difference in the berry color, the berries of TMR4 and 5 are more golden.

*Table 30: Quality results and Quality index calculation with ADR grape type target, for 2011 vintage and for the five TMRs*

| **criterion number** | parameter (scale or unit) | **$c_{iTMR1}$** | **e %** | **$c_{iTMR2}$** | **e %** | **$c_{iTMR3}$** | **e %** | **$c_{iTMR4}$** | **e %** | **$c_{iTMR5}$** | **e %** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **$c_1$** | color (/10) | 3.95 | 50 | 3.40 | 50 | 3.59 | 50 | 5.25 | 100 | 4.16 | 100 |
| **$c_2$** | dominant aroma | Fresh fruit | 50 | Fresh fruit | 50 | Fresh fruit | 50 | Fresh fruit | 50 | Fresh fruit | 50 |
| **$c_3$** | sugar content (pot. %alc.) | 12.31 | 50 | 12.03 | 50 | 11.8 | 50 | 12.28 | 50 | 12.31 | 50 |
| **$c_4$** | rot (%) | 14* | 100 | 0.8 | 100 | 5 | 100 | 2.3 | 100 | 0.6 | 100 |
| **Qg** | Quality index | | 62.5 | | 62.5 | | 62.5 | | 75 | | 75 |

* turning to noble rot

## 3.2 SENSITIVITY ANALYSIS ON $Q_G$

A sensitivity analysis was conducted on Qg by changing the primary quality target from type ADR (Aging Dry wine Ripe aromas) to Type FD (Fresh Dry wine) Table31 reports the quality index calculation results with this new quality target.

*Table31: Quality index calculation on the five TMRs considering grape type FD as primary quality target*

| criterion number | parameter (scale or unit) | $c_{iTMR1}$ | e % | $c_{iTMR2}$ | e % | $c_{iTMR3}$ | e % | $c_{iTMR4}$ | e % | $c_{iTMR5}$ | e % |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $c_1$ | color (/10) | 3.95 | 100 | 3.40 | 100 | 3.59 | 100 | 5.25 | 50 | 4.16 | 50 |
| $c_2$ | dominant aroma | Fresh fruit | 100 | Fresh fruit | 100 | Fresh fruit | 100 | Fresh fruit | 100 | Fresh fruit | 100 |
| $c_3$ | sugar content (pot. %alc.) | 12.31 | 100 | 12.03 | 100 | 11.8 | 100 | 12.28 | 100 | 12.31 | 100 |
| $c_4$ | rot (%) | 14* | 100 | 0.8 | 100 | 5 | 100 | 2.3 | 100 | 0.6 | 100 |
| Qg | Quality index | | 100 | | 100 | | 100 | | 87.5 | | 87.5 |

* turning to noble rot

The sensitivity analysis shows that the grapes of the five TMR5 are more suited to type FD wine than to type ADR as expected initially by the growers. The hierarchy of the TMRs is reverse to the one corresponding to grape type ADR target.

## 3.3 MASS X QUALITY INDEX CALCULATION

The mass-quality index is calculated from $Q_g$ and grape yield : $Q_g$ x Yield (Table32)

*Table32: Mass-quality index ($MQ_g$) calculation for the 5 TMRs for the two quality targets*

| Case | Yield 2011(kg/ha) | Qg 2011 [target ADR (%)] | MQgADR | Qg 2011 [target FD(%)] | MQgFD |
|---|---|---|---|---|---|
| TMR 1 | 6440 | 62.5 | 4025 | 100 | 6440 |
| TMR 2 | 5250 | 62.5 | 3281 | 100 | 5250 |
| TMR 3 | 7500 | 62.5 | 4688 | 100 | 7500 |
| TMR 4 | 5880 | 75,0 | 4410 | 87.5 | 5145 |
| TMR 5 | 5250 | 75,0 | 3938 | 87.5 | 4594 |

The TMRs can be divided in two groups having the same $Q_g$: TMRs 1 to 3 on the one hand and TMRs 4 and 5 on the other hand. The groups were the same for the two quality targets, but changing the quality target induced an inversion in $Q_g$s hierarchy between the two groups.

## 3.4 COMPARISON OF TMR ECO-EFFICIENCY ACCORDING TO THE THREE DIFFERENT FUNCTIONAL UNITS

Due to the huge quantity of data generated by this comparison, we have chosen to present the results for three impact categories that proved to give very different patterns in the results presented in the first paper (part I): Global Warming Potential at term 100 year (GWP 100a), Freshwater Ecotoxicity Potential (FwEtoxP), and non-renewable Resources consumption (Res) (Figure 37). The similar figures on the other six impact categories selected in our research are available in supplemental data, Fig A1.

The results of the comparison between the five TMRs depend on the FU chosen. However, some major tendencies remain stable. The hierarchy is the same between TMRs 1, 3 and 5 for the 3 FUs in the 3 impact categories. TMR1 is still dominating Res patterns, while TMR 3 has the lowest impact for GWP 100a and Res but high for FwEtoxP. TMR5 shows high GWP 100a values, low FwEtoxP and average Res values. TMRs 2 and 4 occupy average positions in the hierarchy for GWP100a and Res. The most important change between the FUs concerned TMR2's GWP 100a and FwEtoxP impacts which were 13 to 30% higher relatively to other TMRs with the $MQ_g$ FU than with the other FUs. This was due to the improvement of the performance of TMRs 4 and 5 relative to the others in the $MQ_g$ FU thanks to their better $Q_g$. Indeed, the higher the $Q_g$, the better the eco-efficiency results in $Q_g$ FU. This is true for the $MQ_g$ FU but modulated by the yield. The yield had the same influence on eco-efficiency: for a same per ha impact, the higher the yield, the better the eco-efficiency for mass and mass quality FUs. Consequently the TMRs which combine high yield and high $Q_g$ have the highest gain in eco-efficiency when changing from 1 ha FU to $MQ_g$ FU.

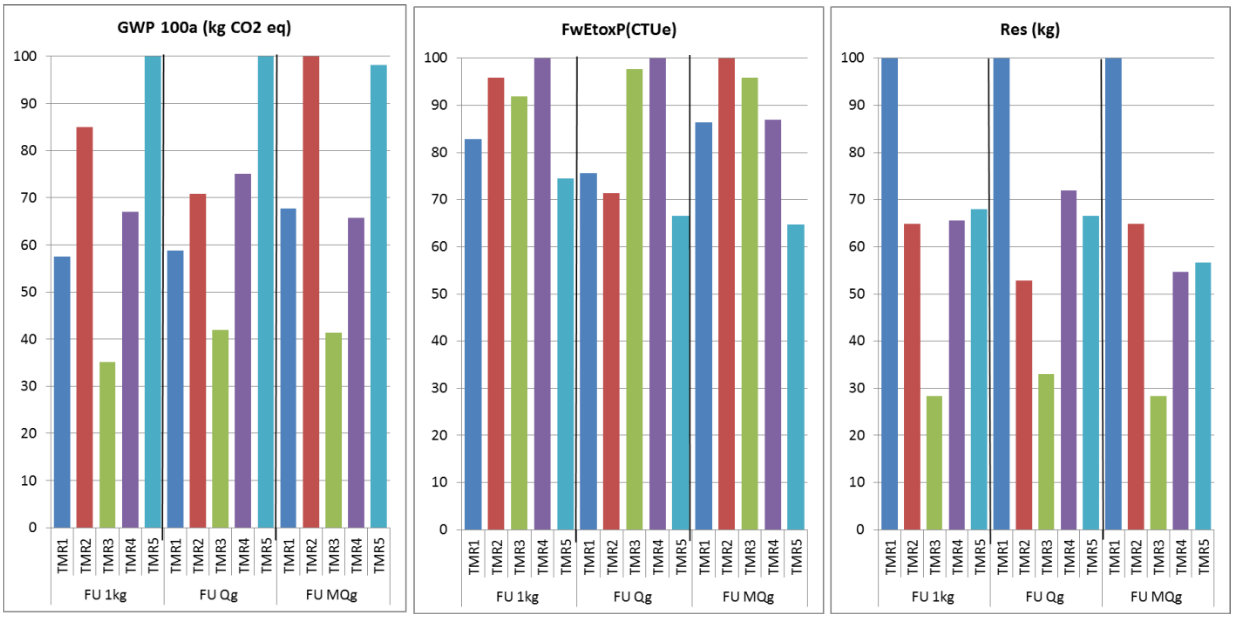

*Figure 37: LCA results of the five TMRs for GWP 100a, FwEtoxP and Res impact categories, according to three different Functional Units (FUs): 1 kg grapes, quality index: Qg, 1 kg grapes xQg: MQg. Results are presented in % of the impact of the most impacting TMR for grape quality target "Ageing Dry wine Ripe aromas" (ADR)*

The TMR 3 cumulated the highest $MQ_g$ and the highest eco-efficiency per ha for GWP 100a and Res.

## 3.5 EFFECT OF CHANGE OF QUALITY TARGET ON ECO-EFFICIENCY RESULTS

The change of grape quality target between "Ageing Dry wine Ripe aromas" (ADR) and "Fresh Dry wines" (FD) is presented for the two qualitative FUs in Figure 38.

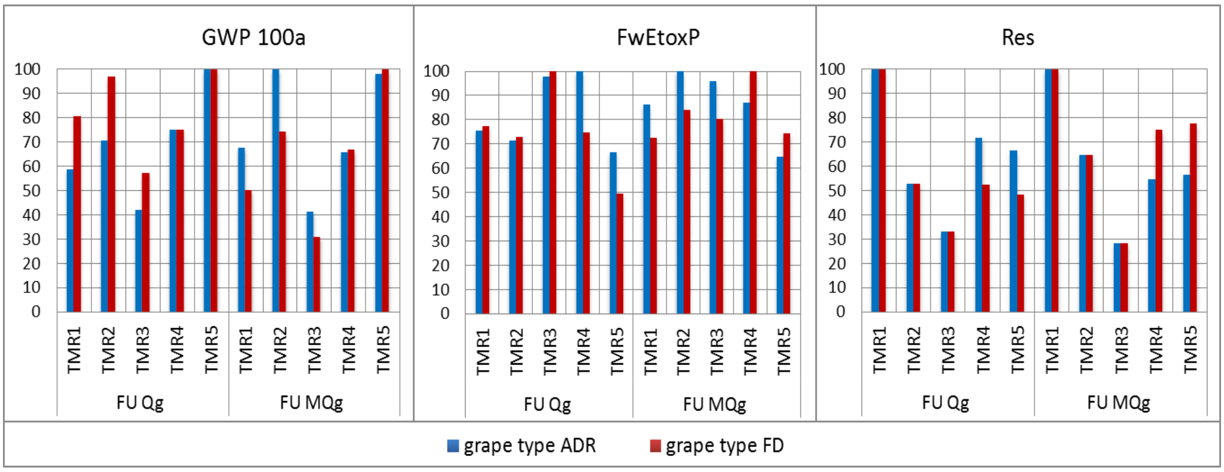

*Figure 38: effect of a change of quality target on eco-efficiency results for the five TMRs and for global warming potential (GWP100a), Freshwater Ecotoxicity potential (FwEtoxP) and Resources use (Res), expressed in Qg Functional Unit (FU) and Mass x Qg FU.*

Once again, the strong domination of TMR 5 on GWP 100a and of TMR1 on Res are not modified. The very good performance of TMR3 on GWP 100a and Res also remains clear, as well as TMR5's good performance on FwEtoxP. The division in two groups of TMRs for Qg value is visible on the charts. Accordingly, the change of pattern due to the modification of target only affects the differences of hierarchy between these two groups but the hierarchy is maintained within the groups.

## 3.6 AN APPROACH OF TMRS QUALITY-ENVIRONMENT TRADE OFF

Aiming to improve TMRs on a double objective of quality and environmental performance corresponds to identifying the best trade-offs between these two aims, unless they prove to be synergic.

We propose the following representation of eco-efficiency per impact category (the same categories as in the previous sections are presented here)

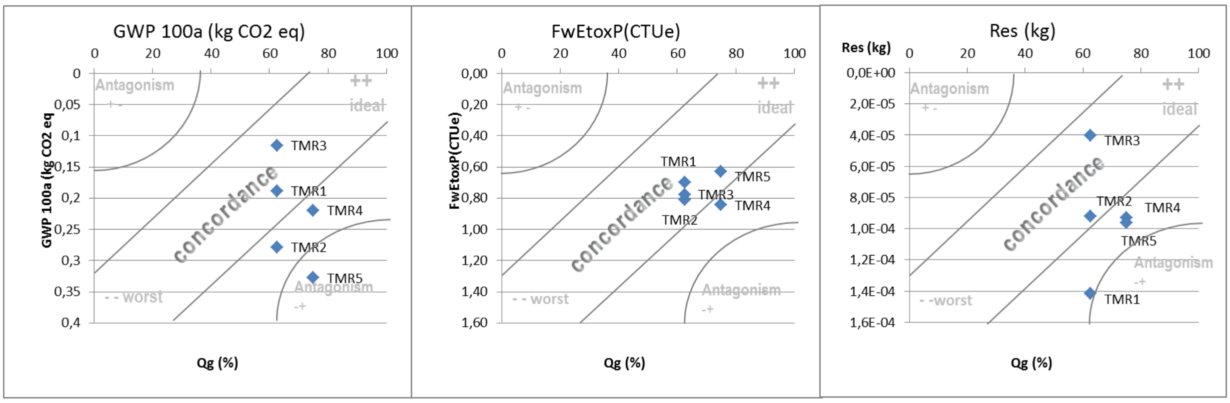

*Figure 39: The five TMRs are placed in eco-efficiency matrixes for GWP100a, FwEtoxP and Res. Environmental impacts are related to 1 kg grapes FU. Qg is related to Ageing Dry wine Ripe aromas (ADR) grape type quality objective.*

This presentation of TMR eco-efficiency gives, logically, the same hierarchy as results of impacts expressed in $Q_g$FU. The maximum values of the scales were chosen relatively to the range of variation in the present study. TMR3 is shown as the most eco-efficient in GWP 100a and Res impact categories, and TMR5 is the most eco-efficient in FwEtoxP impact category.

The limits of antagonism zones are only indicative, to signify tendencies of opposition between quality and environmental objectives. Such an antagonism appears for TMR5 on GWP 100a and For TMR1 on Res. The scales used here are appropriate for comparison in same conditions with the aim of improvement of the TMRs.

However, if one wants to qualify the TMRs in a more absolute way, the scale must be based on more generic value ranges. GWP 100a impact category scale could be changed in accordance with Rugani et al. (2013) who mention on the basis of a review of 29 studies that the average $CO_2$ eq emissions of the grape production phase (including vine planting) of a wine bottle is 0.45 +/- 0.38 kg $CO_2$eq. (Figure 40)

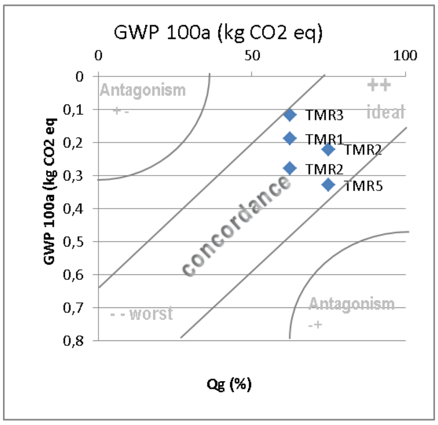

*Figure 40: Eco-efficiency matrix with the 5 TMRs for GWP-100a impact category, with impact scale adapted to international variation range.*

FwEtoxP was previously calculated by Vázquez-Rowe et al.(2012b) and Villanueva-Rey et al. (2014b) in Galicia (Spain). However, pesticide emission calculation are very sensitive to soil and climate conditions (Renaud-Gentié et al. under review), these authors used a previous version of the emission model Pest LCI not adapted to viticulture and the characterization factors for one of the substances dominating FwEtoxP values in their study were recalculated for our research giving much lower impacts. Thus their results are not appropriate to set our scale. The “Res” chart scale could not be changed either due to the absence of comparable references for this impact categories.

# 4 DISCUSSION

## 4.1 THE FIVE TMRS’ QUALITY-RELATED ECO-EFFICIENCIES

The quality index $Q_g$ results for the five TMRs show only minor differences, which are due to berry color. This is mainly caused by the standardization of harvest dates (number of days after veraison) for our research. Additionally, despite the fact that 2011 presented good climatic conditions for ripening, the grapes did not well correspond to the primary target (Aging Dry wine, Ripe aromas) but well corresponded to the secondary target (Fresh Dry wine). One of the winegrowers (TMR3) harvested 2 weeks later than we did for the study and obtained grape characteristics far closer to the ADR objective. Nevertheless, the index Qg is sensitive to this difference and to the change of grape quality target. The TMRs were distributed in two levels of $Q_g$, This resulted in a light evolution of the hierarchy between the TMRs, in the three presented impact categories when the quality target was changed. The most important change concerned mainly TMR2. TMR 3 remained the most eco-efficient for GWP 100a and Res whatever the FU, TMR1 remained the least eco-efficient for Res. TMR4 remained in an average position in GWP 100a and Res impact categories, and TMR5 remained the least eco-efficient for GWP 100a.

## 4.2 GRAPE TYPES DETERMINATION

A grape typology based on expert knowledge elicitation was used to build the quality indicator of correspondence to grape quality target.

The experts described the grape types aromas in terms of dominant aroma corresponding to maturity evolution (green, fresh, ripe overripe). We based the determination of dominant aromas on a list of grape aromas originally generated by the panel for Chenin Blanc grapes, and evaluated on a 0 to 10 scale. This typical framework of wine sensory analysis normally considers that each attribute is independent and evaluated independently. In the case of berries and must, aromas are not independent from each other because very linked to maturity. A continuous scale directly based on dominant aroma from vegetal/green up to overripe would clarify the aromas evaluation.

Sanitary state determination was always done by the same assessor, which made the data reliable, but it is a long assessment and prone to assessor bias when assessor changes (Hill et al. 2014). A more rapid and reliable method as proposed by Hill et al. (2014) could be considered.

## 4.3 CORRESPONDENCE TO TARGET, A NEW WAY TO EXPRESS GRAPE QUALITY

To our knowledge, appreciation of grape quality related to a defined target was not formalized to date in a specific indicator. This process is spontaneously done by the production stakeholders when they harvest or process the grapes, but the targets are often not precisely described, being more an objective fixed on an unconscious scale based on experience. This approach is generic to any grape, provided the criteria and thresholds are adapted to the cultivar and regional, or even local, and annual context.

However, this first proposal of indicator construction might be improved in the future by the use of fuzzy logic (Zadeh 1965), to avoid the threshold effects, and permit a gradual progression of “e” from primary target to secondary ones and refused grapes(Coulon-Leroy et al. 2012; Guillaume and Charnomordic 2012).

## 4.4 THE IMPORTANCE OF QUALITY TARGET AND CORRESPONDENCE GAP “*e*” DETERMINATION

The sensitivity analysis showed the importance of the quality target choice on eco-efficiency results because of their influence on $Q_g$. The correspondence gap “e” between the primary and secondary targets is also an important source of variation of $Q_g$.

***e***=100% is a perfect correspondence to the primary target, ***e***=0% is out of the target considering an unacceptable target. In this study, we fixed the value ***e***=50% for a grape corresponding to an acceptable secondary target, but in other studies this threshold can be adapted. For generic situations, ”***e***” can be determined with the experts that contribute to the determination of grape types and criteria. For specific studies, for example the assessment of a given wine in a cooperative or an estate, “***e***” should be adapted with the final user of the results to each situation, because it can be highly dependent on the economic and commercial structure of the wine estate which determines the difference of commercial value between the primary and secondary target grapes or the corresponding wines.

## 4.5 WHICH QUALITY FUNCTIONAL UNIT FOR WHICH OBJECTIVE?

We have tested two FUs relating to grape quality. The $Q_g$ FU reflects only a quality level, without any reference to the yield. Using this FU reflects that the grape production exclusive - or very primary- objective is quality, whatever the yield. This can be the case in some specific situations (ultra-premium quality wines, or high quality oriented small vineyards that represent a small part of the income of the farm for example). However, in most situations, both quality and yield are important to secure the income from the vineyard activity and to satisfy the markets in terms of number of bottles. The second option, ($MQ_g$), mixing mass and quality, permits to account for both objectives.

## 4.6 INTERESTS AND LIMITS OF QUALITY IN FUNCTIONAL UNITS FOR TMR ENVIRONMENTAL EVALUATION

Table 33 reports the main aspects we propose to account for in the choice of FU in quality viticulture.

*Table 33: interests of four Functional Units for quality grape production TMRs*

| Functional unit | advantage/usage |
|---|---|
| Surface :<br>1ha of vineyard | minimize impacts when cultivating a given surface, account for multi-functionality of viticulture (landscape, ecosystem services),<br>adapted to communication of LCA results to winegrowers |
| Mass :<br>1kg grape | minimize impacts of a mass of grapes,<br>considers the economic importance of yield,<br>adapted to communication of LCA results to consumers |
| Mass with a quality level:<br>1kg grape x Qg | minimize the impacts of a mass of grapes<br>considers the central function of quality wine TMRs,<br>avoids decreasing the quality when improving environmental performance, |
| Quality level :<br>Qg | avoids decreasing the quality when improving environmental performance, |

The use of Quality FUs in the assessment of TMR environmental performance improvement presents the advantage that the advisor or the decision maker keeps in mind the quality objective of the production. These FUs are more appropriate than mass and surface FUs in considering the central function of grape production, especially in premium wines production context like PDOs. The MQg FU seems the most relevant in most quality wine production situations because it accounts for both yield and quality objectives. However, surface-based FUs are complementary to quality FUs to account for multi-functionality of viticulture, and also to communicate the results to the producers in a unit that meets their usual technical decision unit, 1 ha. These FUs can’t replace totally per ha FU for another reason, the variability of grape composition due to climatic conditions (Jones and Davis 2000). A climatic accident (like a heavy rain before harvest) can even cause a severe decrease of grape quality which can’t be attributed to the TMR. In this last case, yield and surface FUs will be more reliable than MQg FU. Moreover, yield also varies for climatic reasons (Makra et al. 2009), so MQgFU cumulates two sources of variations linked to climatic conditions (which can be different climatic events for yield and grape) quality.

Accordingly, before planning important changes in the TMR on the basis of LCA results, results must be considered in the climatic context of the year in which they were obtained. The climate of the year must be characterized and related to averages and variation ranges on more than a decade (Coulon et al. 2011). We observed in the Middle Loire Valley (Renaud-Gentié et al. 2014c), as other authors in other regions (Vázquez-Rowe et al. 2012b) or for other perennial productions (Bessou et al. 2014) that the climate of the year is an important variation factor in different aspects accounted in LCA: the TMR itself is adapted to the climatic conditions by the growers, both yield and product quality fluctuate. Hence to get a clear idea of the TMR performance, LCA must be conducted on more than one year, contrasted in a climatic point of view (Renaud-Gentié et al. 2014c) unless a way is found to simulate the effects of climate on these different parameters.

## 4.7 QUALITY RELATED ECO-EFFICIENCY AND TMR ECO-CONCEPTION

Relating LCA results to the quality index Qg can also be done through the eco-efficiency matrix proposed in sections 2.6 and 3.6. This presentation gives the same eco-efficiency hierarchy between the TMRs, but it presents the advantage of visualizing separately the effects of quality and environmental performances on the eco-efficiency. The matrix was also divided in indicative parts related to the degree of convergence of quality and environmental performances. However, positioning the TMRs relatively to these parts of the matrix necessitates a correct adjustment of the scale for each environmental impact category. This could be done here only for global warming potential, thanks to reference data from literature. This scale can also be adjusted with stakeholders regarding their environmental performance progress objectives.

In a perspective of eco-conception, this matrix can be a useful tool to compare effects of scenarios of TMR improvement or of innovative TMRs. However, up to now, TMR eco-conception considering quality is not possible because Qg cannot be predicted. A model predicting Qg change according to technical choices and its range of variations due to climate is necessary for this purpose (Beauchet et al. 2014a).

# 5 CONCLUSION

We proposed a new grape quality assessment approach for inclusion in eco-efficiency assessment of quality vineyard technical management routes. The quality indicator Qg expresses the degree of correspondence of the harvested grapes to the quality target assigned to the TMR. A typology of grapes was established with experts as a basis for this Qg indicator. The five contrasted vineyard TMRs, representing the Middle Loire Valley diversity proved to give different quality-based eco-efficiency performances close to those obtained with classical FUs (1 kg and 1 ha vines.1year) due to minor differences in Qg.

Two functional units for life cycle assessment of TMRs were derived from this indicator. A quality FU: Qg, and a mass x quality FU: MQg including the yield. QgFU alone appeared too restrictive while including the yield in this quality FU allowed accounting for the main function of the system, the production of a given quantity of quality grapes for a given type of wine. Even if PDO wines are not responding to industrial quality standards, the wine growers and winemakers have in mind a quality target which is adjusted every year to the quality potential given by the vintage conditions. This adjustment of the quality target can be done whenever necessary. However including quality in TMR evolution or eco-conception demands further work for inclusion of fuzzy logic in the indicator construction to avoid threshold effects, for grape quality prediction knowing the TMR.

Finally, we propose an eco-efficiency matrix to compare the eco-efficiency hierarchy between the TMRs and to visualize separately the effects of quality and environmental performances on the eco-efficiency. This matrix was also divided in indicative parts related to the degree of convergence of wine quality and environmental performances to evaluate the trade-offs between these two main objectives for any winegrower. Relating environmental burdens and Qg in this eco-efficiency matrix gave interesting perspectives for result communication to stakeholders.

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# SUPPLEMENTARY MATERIAL

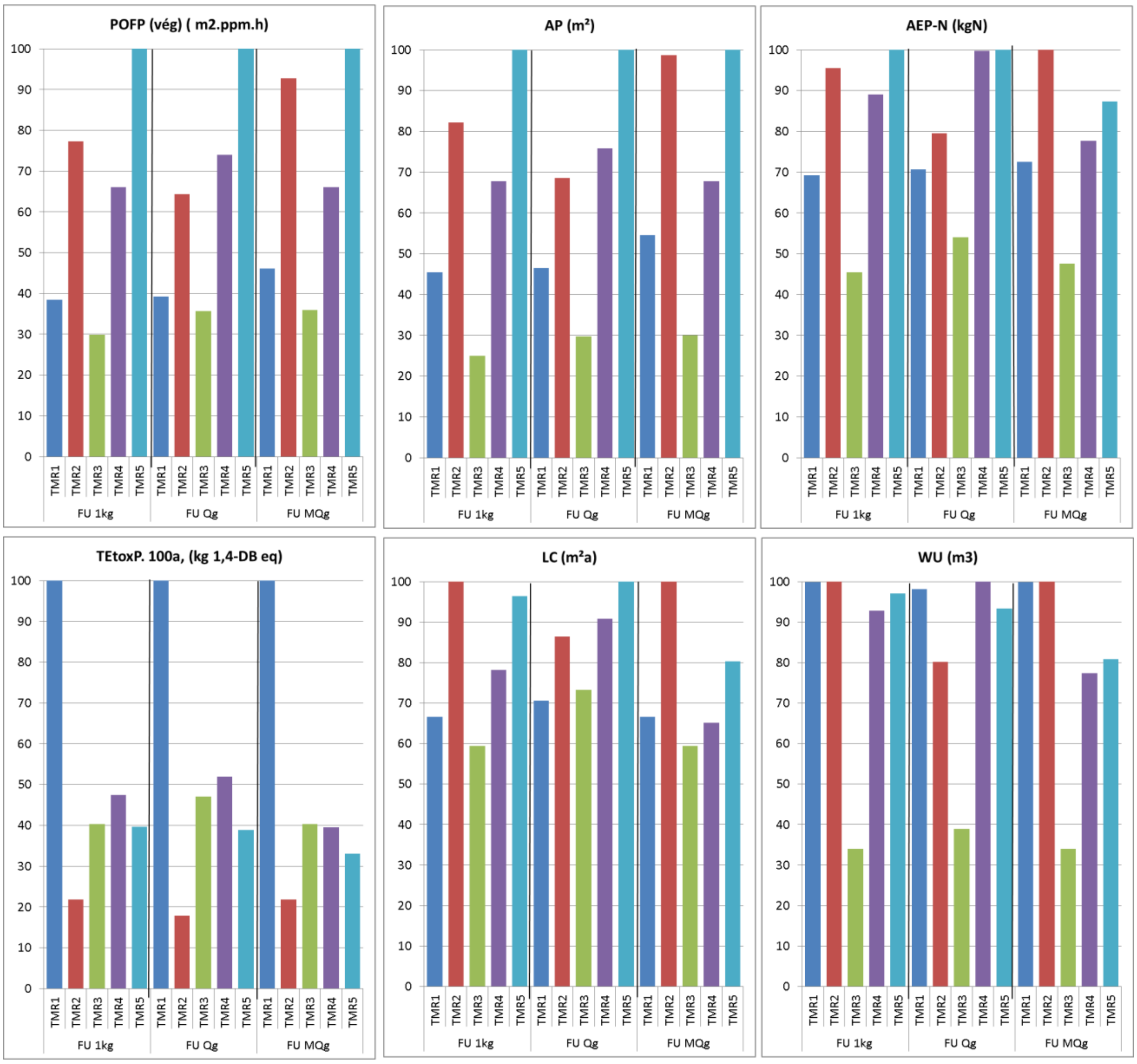

Figure A1: Eco-efficiency results of the five TMRs for Photochemical ozone formation potential (POFP) , Acidification potential (AP), Aquatic Eutrophication potential linked to nitrogen (AEP-N), Terrestrial Ecotoxicity potential in term 100 years (TEtoxP 100a), Land competition (LC), and Water Use (WU) impacts, according to three different FUs: 1 kg grapes, quality index: Qg, 1kg grapes xQg: MQg. Results are presented in % of the impact of the most impacting TMR.

# SYNTHESE

Ce chapitre avait pour objectif de proposer une première approche d'inclusion de la qualité du raisin dans l'évaluation de l'éco-efficience des ITKv et de la tester sur les 5 ITKv contrastés sélectionnés au chapitre 1.

Nous avons proposé un indicateur de qualité original, $Q_g$, basé sur le degré de correspondance à un objectif qualitatif, exprimé en termes de type de raisin décrit par des critères donnés par des experts.

Cet indicateur a pu être décliné en deux unités fonctionnelles (UF) utilisées dans l'ACV : l'indice lui-même et le kilogramme de raisin affecté de ce degré de correspondance à l'objectif qualitatif. Cette dernière UF a permis d'exprimer le plus directement la fonction première de l'ITKv en AOC : produire une quantité donnée de raisins d'une qualité optimale. Une matrice d'éco-efficience a aussi été proposée pour lier la qualité exprimée par l'indicateur $Q_g$ et la performance environnementale d'un kg de raisin ou d'un ha de vignoble. Elle apparaît comme un outil de communication intéressant pour les acteurs de la filière viticole.

Les niveaux qualitatifs des cinq ITKv ont montré des écarts assez faibles, amenant à peu de changements dans la hiérarchie des cinq ITKv entre les performances environnementales exprimées par UF Qualité ou UF Masse x Qualité par rapport à l'UF Masse (1kg de raisin).

Cet indicateur se montre sensible au changement d'objectif qualitatif, mais présente la limite d'être basé sur une combinaison de variables discrètes et de ce fait, de présenter des effets de seuil, il faudra donc dans un deuxième temps avoir recours à la logique floue pour permettre une notation des aspects qualitatifs du raisin sur une échelle continue.

Par ailleurs, l'évaluation de la qualité des raisins est basée une évaluation ex post à partir des données mesurées à la récolte. Ellet ne permet donc pas de réaliser une analyse ex ante de l'éco-efficience, basée sur une qualité potentielle. Une analyse de scenarios prospectifs nécessite une approche de modélisation de la qualité à partir des pratiques viticoles et du milieu (climat sol et sous-sol).

# CHAPITRE 7 : DISCUSSION GENERALE

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La question de recherche de la thèse était la suivante :

**Dans quelles conditions l'ACV est-elle une méthode appropriée à l'évaluation environnementale des itinéraires techniques viticoles de production de raisins de qualité à l'échelle parcellaire à des fins de choix des techniques?**

Dans cette partie, nous allons, après la synthèse des principaux résultats obtenus, discuter les questions méthodologiques puis dessiner des perspectives avant de conclure

## 1 SYNTHESE DES PRINCIPAUX RESULTATS

**Nous avons tenté de répondre à notre question de recherche à travers cinq objectifs principaux :**

**Le premier objectif a consisté à choisir des cas d'étude contrastés d'un point de vue des itinéraires techniques**, visant un même objectif qualitatif de production de vin et représentant la diversité régionale des itinéraires. Nous avons concentré notre étude de cas sur les conduites de vignobles visant l'élaboration de vins blancs secs d'AOC issus de cépage Chenin en Moyenne Vallée de la Loire. Ce choix visait à disposer d'un matériau permettant de tester et de mettre au point un cadre méthodologique d'ACV adapté à l'échelle de la parcelle et à l'objet « itinéraire technique » en vue du choix de pratiques viticoles.

Afin d'y répondre, nous avons établi une méthode spécifique, Typ-iti, permettant de modéliser la diversité des itinéraires techniques d'un échantillon de parcelles, d'identifier les grands types d'itinéraires (ITKv), de les caractériser par des pratiques et des associations de pratiques spécifiques, et d’identifier des cas d'études représentatifs de cette diversité (Renaud-Gentié et al. 2014a).

Au moyen de cette méthode, la diversité des ITKv du vignoble de Chenin blanc pour vins blancs secs d’AOC en moyenne Vallée de la Loire a été modélisée en cinq groupes d'ITKv partitionnés principalement sur les choix techniques de protection phytosanitaire, d’entretien du sol, et de mode de récolte. Ces 5 groupes ont été désignés par les pratiques dominantes. Trois groupes relèvent de la viticulture conventionnelle et deux de la viticulture biologique.

Nous avons pu choisir cinq ITKv mis en œuvre par des vignerons sur des parcelles réelles et représentant ces cinq groupes. Ces ITKv ont alors fait l'objet d'un inventaire du cycle de vie ainsi que de prélèvements de raisins à maturité pour caractériser leur qualité pour le millésime 2011.

**Le deuxième objectif visé était la mise en place d'un cadre méthodologique d'ACV** adapté à l'évaluation des itinéraires techniques viticoles et des pratiques à l'échelle de la parcelle en ayant résolu la question de l'intégration des émissions de pesticides au champ.

Le modèle de calcul des émissions au champ de pesticides agricoles organiques PestLCI a été adapté aux spécificités viticoles grâce à une collaboration avec ses concepteurs (chapitre 2). De nombreux éléments propres à la vigne ont pu y être inclus, ce qui permet une modélisation au plus près de la situation réelle. Nous avons pu ainsi calculer les émissions des pesticides organiques pour les parcelles du réseau. Les impacts potentiels de ces émissions de pesticides sur les organismes aquatiques d'eau douce ont pu être calculés grâce à l'ajout de facteurs de caractérisation spécifiques aux substances actives utilisées en viticulture dans la base de données USETox$^{TM}$. Les matières actives organiques les plus utilisées en viticulture en France (Ambiaud 2012b) seront ainsi prochainement disponibles dans ces deux modèles. Par contre, à ce jour, aucun modèle d'émission ni de caractérisation n'est capable de prendre en compte le comportement des substances actives inorganiques (notamment cuivre et soufre), il s'agit là d'un chantier prioritaire pour la filière viticole mais conséquent en termes d’investissement à envisager pour le futur.

Le cadre méthodologique de l'ACV répondant à l'objectif d'évaluation des itinéraires techniques viticoles a été établi et proposé dans le chapitre 3. Il définit les frontières du système étudié (du berceau à la porte du champ), la prise en compte des phases non productives et des opérations occasionnelles, les unités fonctionnelles, les postulats posés pour l'inventaire des flux, les modèles d'émission directes sélectionnés afin de se rapprocher au plus près des conditions spécifiques au site, puis le choix des méthodes de caractérisation et les impacts sélectionnés. Les éléments restant à améliorer pour un calcul d'éco-efficience au plus près de la réalité de la situation étudiée ont été identifiés.

**Le troisième objectif de la thèse était de vérifier l'adéquation de la méthode ACV à l'objectif d'évaluation et d'amélioration des ITKv à l'échelle parcellaire** par une mise en œuvre sur les cinq cas contrastés.

Le calcul de l'éco-efficience par l'ACV des cinq ITKv contrastés pour le millésime 2011 (chapitre 3) a permis :

- d'identifier les pratiques les plus contributives à chacun des 9 impacts sélectionnés, et ce y compris parmi les phases non productives, à savoir (moyennant des variations entre les ITKv) i) les phases consommatrices de gasoil (consommation de ressource non renouvelable et émissions de polluants liées à sa combustion) comme l’entretien mécanique du sol et du feuillage, les traitements ou les vendanges mécaniques ii) le palissage de la vigne à cause de l’utilisation d’acier galvanisé pour les fils et parfois pour les piquets et le transport des piquets sur de longues distances iii) l’utilisation de certains intrants générant des émissions polluantes ou écotoxiques lors de leur fabrication ou au champ (fertilisants et produits phytosanitaires comme l’Aclonifen ou le Cymoxanil).

- d'accéder à l'explication de ces contributions en identifiant les processus ou substances responsables et les étapes du cycle de vie concernés (à la parcelle, lors des processus amont, ou aval).

- le test de solutions alternatives dont le gain environnemental a été quantifié : L’effet d’un changement de matériaux de palissage (piquets de bois d’acacia au lieu d’acier galvanisé ou pin autoclavé et fils polyester au lieu de fils d’acier galvanisé) et d’origine géographique des piquets (acacia local au lieu de Hongrie) permettrait une diminution d’impact/ha atteignant 19% de GWP-100a, 27% d’AP, et 76% de Res .

- une comparaison des cinq ITKv du point de vue de leur éco-efficience globale pour les unités fonctionnelles choisies : 1ha de vigne en production cultivé durant 1 an, 1kg de raisin, % de concordance à l’objectif de qualité visé (chapitre 4), 1kg de raisin affecté d’un % de concordance à l’objectif de qualité visé (chapitre 4). L’ITKv3, représentant le groupe 3 « traitement de synthèse et interventions minimaux » est apparu comme la conduite la plus éco-efficiente pour toutes les UF pour toutes les catégories d’impacts, excepté les écotoxicités terrestre et aquatique d’eau douce. L’ITKv1 représentant le groupe «traitement systématiquement de synthèse et travail manuel limité », présente la deuxième éco-efficience sur la plupart des catégories d’impacts et concernant l’utilisation de ressources non renouvelables. De même L’ITKv5 (pour le groupe 5 « biologique intensif »), est très performant pour l’écotoxicité et l’utilisation de ressources mais le plus impactant concernant les catégories d’impact sensibles à la consommation de carburant : potentiel de réchauffement climatique à 100 ans, acidification et production d’ozone troposphérique. Les ITKv 2(pour « usage modéré de traitements ») et 4 (pour « biologique modéré ») affichent des performances assez proches et basses à moyennes selon les catégories d’impact.

- une comparaison des contributions des pratiques entre les itinéraires afin d'identifier les choix techniques les plus éco-efficients et envisager les possibles applications de ces techniques aux autres ITKv, comme l'utilisation d'un quad pour certaines opérations ou la limitation du nombre de passages pour certains travaux mécanisés, ou encore les solutions de palissage évoquées ci-avant.

**Le quatrième objectif était d'observer le potentiel de variation des résultats dû au millésime.** Nous y avons répondu par le biais d'une ACV comparative pour deux millésimes contrastés, 2011 et 2013 (chapitre 4) du point de vue climatique et du niveau de pression parasitaire de l'ITKv3. L'effet millésime constaté sur l'éco-efficience est de l'ordre de 12 à 30 % pour les impacts les plus liés à l'intensité des interventions au vignoble. Même si une comparaison à l'ensemble des résultats des cinq ITKv de 2011 montre que l'ITKv3 même en année défavorable, demeure parmi les plus éco-efficients pour la grande majorité des catégories d'impact, une comparaison de l'ensemble des cinq ITKv en 2013 à ceux de 2011 permettra de voir en quoi la hiérarchie observée en 2011 est modifiée par la différence de millésime. En effet, selon Barbeau (2008), tous les milieux n'ont pas la même amplitude de réaction aux conditions climatiques du millésime, ce qui pourrait se traduire dans des différences d'ajustement des pratiques au millésime, si les viticulteurs sont réactifs à cette variabilité.

Il est donc important de prendre en compte la variabilité potentielle de l'éco-efficience due au millésime notamment dans les évaluations environnementales visant à des choix techniques de moyen ou long terme, l'établissement de références ou l'affichage environnemental. Ceci confirme, pour les conditions de la viticulture de qualité en Moyenne Vallée de la Loire, les résultats de Vázquez-Rowe et al. (2012b) et des récents travaux de Bessou et al. (2014) et Alaphilippe et al.(2014). L'accentuation possible des aléas climatiques, instruite par les chercheurs du GIEC lors de leurs recherches sur les dérégulations climatiques globales (IPCC 2014) risquent de rendre ce fait encore plus structurant dans le travail futur des agronomes.

**Le cinquième objectif consistait à proposer une prise en compte de l'objectif de qualité du raisin assigné à l'ITKv dans le processus d'amélioration de ses performances environnementales**. Nous avons choisi de tester, comme une première approche de cette question, l'inclusion de l'objectif qualitatif dans l'unité fonctionnelle de l'ACV et l'établissement d'une matrice d'éco-efficience (chapitre 5). En effet, l'ACV doit être conduite relativement à la fonction du produit que l'on souhaite évaluer. Or, la fourniture d'un raisin de qualité pour un rendement dont le maximum est défini par le cahier des charges de l'AOC est la fonction première de l'ITKv en conditions d'AOC.

La détermination des types de raisins ciblés par les vignerons pour les ITKv étudiés, et leur description par des experts, nous a permis de construire un indicateur de qualité $Q_g$ exprimant l'adéquation du raisin récolté à la cible qualitative visée par les producteurs.

Cet indicateur ainsi qu'une combinaison entre masse et qualité ont été pris comme unité fonctionnelle (UF) pour l'ACV. Les résultats de l'ACV exprimés relativement à ces deux UF ont donné une hiérarchie peu modifiée des TMR par rapport aux UF 1ha et 1kg pour l’ensemble des ITKv (Tableau 34) excepté l’ITKv2. En effet, l’ITKv2 montre de bonnes performances environnementales pour fournir un niveau de qualité donné (UF $Q_g$), mais son éco-efficience est mauvaise pour une UF combinant masse et qualité dans une majorité de catégories d’impacts.

*Tableau 34 : Comparaison de la hiérarchie des performances environnementales des 5 ITKv (du vert : meilleure performance, au rouge, moins bonne performance) pour les 9 catégories d’impact étudiées. entre les quatre Unités Fonctionnelles : 1ha de vignoble, 1kg de raisin, $Q_g$ : indice de qualité du raisin, $MQ_g$ : 1kg de raisin x $Q_g$*

| | Unit | GWP 100a (kg CO2 eq) | POFP (vég) ( m2.ppm.h) | AP (m²) | EP N (kgN) | TEtox. 100a, (kg 1,4-DB eq) | FwEtoxP (CTUe) | Res (kg) | WU(m3) | LC (m²a) |
|---|---|---|---|---|---|---|---|---|---|---|
| FU 1ha | TMR1 | 1212 | 13146 | 188 | 6 | 1,7 | 4500 | 0,9 | 12199 | 9 |
| | TMR2 | 1461 | 21561 | 277 | 7 | 0,3 | 4248 | 0,5 | 14927 | 7 |
| | TMR3 | 864 | 11930 | 120 | 5 | 0,8 | 5817 | 0,3 | 12659 | 3 |
| | TMR4 | 1290 | 20659 | 256 | 7 | 0,8 | 4962 | 0,5 | 13079 | 7 |
| | TMR5 | 1720 | 27915 | 337 | 7 | 0,6 | 3300 | 0,5 | 14394 | 7 |
| FU 1kg | TMR1 | 1,9E-01 | 2,0E+00 | 2,9E-02 | 9,5E-04 | 2,7E-04 | 7,0E-01 | 1,4E-04 | 1,9E+00 | 1,4E-03 |
| | TMR2 | 2,8E-01 | 4,1E+00 | 5,3E-02 | 1,3E-03 | 5,9E-05 | 8,1E-01 | 9,2E-05 | 2,8E+00 | 1,4E-03 |
| | TMR3 | 1,2E-01 | 1,6E+00 | 1,6E-02 | 6,2E-04 | 1,1E-04 | 7,8E-01 | 4,0E-05 | 1,7E+00 | 4,7E-04 |
| | TMR4 | 2,2E-01 | 3,5E+00 | 4,3E-02 | 1,2E-03 | 1,3E-04 | 8,4E-01 | 9,3E-05 | 2,2E+00 | 1,3E-03 |
| | TMR5 | 3,3E-01 | 5,3E+00 | 6,4E-02 | 1,4E-03 | 1,1E-04 | 6,3E-01 | 9,6E-05 | 2,7E+00 | 1,3E-03 |
| FU Qg | TMR1 | 758 | 8216 | 117 | 4 | 1,1 | 4500 | 0,6 | 7624 | 6 |
| | TMR2 | 913 | 13476 | 173 | 4 | 0,2 | 4248 | 0,3 | 9330 | 5 |
| | TMR3 | 540 | 7456 | 75 | 3 | 0,5 | 5817 | 0,2 | 7912 | 2 |
| | TMR4 | 967 | 15494 | 192 | 5 | 0,6 | 4342 | 0,4 | 9809 | 6 |
| | TMR5 | 1290 | 20936 | 253 | 5 | 0,4 | 2888 | 0,4 | 10795 | 5 |
| FU MQg | TMR1 | 3,0E-01 | 3,3E+00 | 4,7E-02 | 1,5E-03 | 4,3E-04 | 7,0E-01 | 2,3E-04 | 3,0E+00 | 2,2E-03 |
| | TMR2 | 4,5E-01 | 6,6E+00 | 8,4E-02 | 2,1E-03 | 9,4E-05 | 8,1E-01 | 1,5E-04 | 4,5E+00 | 2,2E-03 |
| | TMR3 | 1,8E-01 | 2,5E+00 | 2,6E-02 | 1,0E-03 | 1,7E-04 | 7,8E-01 | 6,4E-05 | 2,7E+00 | 7,5E-04 |
| | TMR4 | 2,9E-01 | 4,7E+00 | 5,8E-02 | 1,6E-03 | 1,7E-04 | 9,6E-01 | 1,2E-04 | 3,0E+00 | 1,7E-03 |
| | TMR5 | 4,4E-01 | 7,1E+00 | 8,6E-02 | 1,8E-03 | 1,4E-04 | 7,2E-01 | 1,3E-04 | 3,7E+00 | 1,8E-03 |

*correspondant respectivement au groupe :1-«traitement systématique de synthèse et travail manuel limité », 2 « usage modéré de traitements », 3 « traitements de synthèse et interventions minimaux », 4 « biologique modéré » et 5 « biologique intensif ».

GWP 100a : potential de réchauffement climatique à 100 ans, POFP (veg): potential de formation d’ozone photochimique, AP: potentiel d’acidification, AEP-N: potentiel d’eutrophisation lié à l’azote, TEtoxP 100a: potentiel d’écotoxicité terrestre hors pesticides (sauf métaux lourds) à 100 ans, FwEtoxP: potentiel d’écotoxicité pour les organismes aquatiques d’eau douce, Res: comsommation de ressources abiotiques, LC: utilisation d’espace, WU: utilisation d’eau

L'index $Q_g$ s'est par ailleurs montré sensible au type de raisin ciblé, ce qui a influé ainsi fortement sur les résultats ACV et la hiérarchie d’éco-efficience des itinéraires

# 2 DISCUSSION METHODOLOGIQUE

## 2.1 GENERICITE REGIONALE DES RESULTATS D'ECO-EFFICIENCE

Ce travail ne visait pas à établir une vision territoriale de l'impact environnemental de la viticulture. Toutefois, la question de la généralisation des résultats obtenus sur les cas aux autres itinéraires techniques de production de vin blanc sec AOC de Chenin blanc en moyenne Vallée de la Loire, se pose dans l'objectif de leur utilisation sur le terrain par les agents de conseil comme valeurs de référence pour un conseil à la parcelle.

Le choix des cinq cas d'étude obtenus par la méthode Typ-iti permet d'évaluer la généricité des résultats obtenus dans la zone d'étude. Chaque ITKv retenu met en œuvre toutes les opérations techniques caractéristiques du groupe issu de la typologie des ITKv qu'il représente, à l'exception de deux opérations sur onze pour le ITKV3 (« hauteur de rognage » supérieure : sans conséquence sur les impacts environnementaux, sauf si elle implique un système de palissage plus important, ce qui n'est pas le cas ici et un « nombre de traitements phytosanitaires en année difficile » légèrement supérieur). Concernant ce dernier, malgré un nombre d'interventions supérieurs à la moyenne du groupe qu'il représente, l'ITKv3 se montre le moins impactant des cinq ITKv pour les impacts liés à l'intensité des interventions. La généricité de l'ITKv2 doit aussi être nuancée du fait de la très grande hétérogénéité du groupe 2 qu'il représente, et qui se traduit dans le faible nombre de pratiques caractéristiques de ce groupe et l'absence de règles d'association fréquentes entre les pratiques. A contrario, les résultats obtenus pour les ITKv 1, 4 et 5, peuvent être considérés comme très représentatifs des conduites rattachées aux groupes correspondants.

La généricité de ces résultats concerne uniquement les catégories d'impacts non liés aux spécificités du milieu comme le réchauffement climatique (GWP 100a), la formation d'ozone photochimique (POFP), la consommation de ressources non renouvelables (Res), l'utilisation d'espace (LC), et d'eau (WU). Pour les catégories d'impact liées aux calculs d'émissions directes, comme l'acidificationd e smilieux (AP), l'eutrophisation aquatique (AEP-N), l'ecotoxicité terrestre (TETox-P 100a) ou l'ecotoxicité aquatique eau douce (FwEtoxP), les résultats ne peuvent être extrapolés qu'à des parcelles présentant des conditions de milieu comparables.

Cette généricité est aussi à moduler par des éléments qui n'étaient pas inclus dans la typologie des ITKv initiale et qui sont susceptibles d'induire des variations entre ITKv d'un même cluster comme la nature des matériaux de palissage, la toxicité des matières actives utilisées, les doses de fertilisants et amendements ou encore la durée de passage pour une même opération.

## 2.2 MODELISER LES EMISSIONS DIRECTES AU PLUS JUSTE

Afin d'ajuster le cadre méthodologique de l'ACV à notre objectif, nous avons sélectionné les modèles de calculs d'émissions directes les plus avancés et les plus à même de prendre en compte la spécificité du site et des pratiques. Trois points particuliers, liés à de fortes contributions aux impacts méritent particulièrement discussion et poursuite de l'amélioration, il s'agit des pesticides, de l'Azote et du carburant.

### 2.2.1 LES PESTICIDES

La modélisation des émissions de pesticides au champ a fait l'objet d'un travail approfondi dans cette thèse, aboutissant à un modèle d'émissions des pesticides organiques bien ajusté à la viticulture à l'échelle parcellaire. Toutefois, si elle est résolue pour les substances actives organiques (avec cependant la limite de la non prise en compte des métabolites de dégradation), la question ne l'est pas pour les substances actives inorganiques. En effet, le modèle de calcul des émissions de pesticides au champ (PestLCI 2.0), bien qu'étant le plus avancé dans ce domaine ne prend pas en charge les substances actives inorganiques. Le cuivre et le soufre, substances actives ultra-majoritaires en viticulture biologique, mais utilisées aussi en viticulture conventionnelle, sont des inorganiques ainsi que certaines substances actives de synthèse utilisées en viticulture conventionnelle. Le cuivre a été pris en compte dans notre cadre méthodologique en tant qu'élément trace métallique par le modèle d'émissions SALCA-ETM, toutefois l'assomption de 100% du cuivre appliqué atteignant le sol n'est pas cohérente avec celle utilisée pour les autres substances actives via le modèle d'émission Pest LCI 2.0. Il y a donc probablement une surestimation de la quantité de cuivre émis dans les compartiments considérés par SALCA-ETM comparativement aux substances organiques. Les émissions de soufre et des autres pesticides inorganiques ont dû être exclues de l'ACV du fait de l'absence de moyen de les quantifier. La création d'un (ou plusieurs) modèle(s) capable(s) de calculer les émissions des pesticides inorganiques est donc une priorité pour la juste prise en compte des impacts liés aux émissions de pesticides dans les ACV viticoles, et plus largement agricoles, notamment concernant la viticulture biologique. Toutefois, il s'agit d'un travail d'ampleur, nécessitant une expertise de chimiste du fait de la complexité des phénomènes chimiques et biologiques en jeu, qui, de plus, diffèrent entre les différents types de substances inorganiques.

### 2.2.2 L'AZOTE

La prise en compte des émissions d'azote demeure un défi dans les ACV des cultures (Liao et al. 2014). Pour bien prendre en compte l'effet des pratiques pour plus de précision et de fiabilité de la comparaison des ITKv, elle nécessite un approfondissement qui n'a pu être inclus dans le périmètre de cette thèse.

Le lessivage du $NO_3$- sous la vigne a été calculé par le modèle SQCB, comme dans le cadre du projet AGRIBALYSE®. Cependant, l'application d'un modèle tenant compte de la saisonnalité des prélèvements et du climat, ainsi que de la présence d'un enherbement est nécessaire pour plus de précision . Les modèles utilisés par Thiollet-Scholtus et Bockstaller (2015) dans le calcul des indicateurs Indigo Vigne et par Bellon-Maurel et al.(2014) mériteront d'être testés comparativement à SQCB.

Comme le soulignent Meier et al.(2015), l'utilisation d'un modèle (IPCC 2006) basé sur un facteur d'émission unique pour le calcul des émissions de $N_2O$ de la parcelle ne permet pas la prise en compte de la variabilité liée aux conditions de milieu, à la nature des résidus de culture (Gabrielle *et al.*, 2006) et à celle des fertilisants, notamment les engrais organiques dont l'azote contribue moins aux émissions que celui des engrais minéraux (Meier et al. 2012). Par ailleurs Garland et al. (2011) mentionnent un fort effet de l'enherbement du vignoble sur ces émissions.

Les calculs d'émissions de $NH_3$ se heurtent, quant à eux, à un manque de données concernant les valeurs d'Azote ammoniacal pour certains engrais organiques. Certaines valeurs ont été publiées dans le rapport méthodologique AGRIBALYSE® (Koch and Salou 2014) mais la constitution d'une base de données plus complète et accessible serait très utile.

### 2.2.3 LES EMISSIONS LIEES A LA COMBUSTION DU CARBURANT.

Les émissions de COVNM, $NO_x$ et CO issues de la combustion du diesel ne sont pas uniquement proportionnelles aux quantités de carburant consommées, elles dépendent notamment de la puissance du moteur et de la vitesse d'avancement du tracteur. Nous ne disposons pas de ces informations pour les opérations viticoles, et avons dû baser les calculs des émissions sur des valeurs issues d'Ecoinvent (Nemecek et al. 2007) en établissant des correspondances entre les opérations liées aux grandes cultures présentées dans Ecoinvent, et les opérations viticoles. Les autres émissions liées à la combustion du diesel sont directement proportionnelles à la consommation de carburant ; or, les données concernant les consommations de carburant par opération ne pouvant être obtenues de manière fiable auprès des viticulteurs, des valeurs standard par opération ont été utilisées. Cependant, les données de consommation de carburant issues de bancs d'essai disponibles (Gaviglio 2010a) sont incomplètes pour brosser l'ensemble des pratiques en jeu dans les ITKv concernés. Des estimations de consommation ont donc dû être réalisées par extrapolation des données disponibles. Disposer des données précises d'émissions de COVNM, $NO_x$ et CO pour chaque opération viticole est peu envisageable dans l'immédiat. L'incertitude qui découle de ces deux éléments devra donc être quantifiée par le biais d'analyses de sensibilité. Une base de données nationale, voire internationale de consommation de carburant par opération viticole ou agricole devrait être mise en place et alimentée par les différents détenteurs de données prêts à contribuer.

## 2.3 FACILITER ET FIABILISER LE RECUEIL DE DONNEES.

La phase d'inventaire est une des étapes les plus lourdes de l'ACV, notamment lorsque l'on travaille sur des cas réels et à l'échelle parcellaire. Le recueil et la saisie des données primaires et secondaires a nécessité, pour les résultats présentés ici de nombreux mois de travail. Des propositions pour l'allègement de cette phase ont été récemment faites par Bellon-Maurel et al. (2014), via l'utilisation des documents de traçabilité des exploitations. Dans le cadre de notre étude, ces éléments se sont toutefois avérés complétés de manière hétérogène par les exploitants, voire absents quelquefois (pour des exploitations qui de ce fait n'ont finalement pas été retenues dans l'étude). Il est alors nécessaire de proposer aux exploitants concernés par le projet d'ACV ce cadre de collecte de données en amont de la saison de production pour s'assurer de pouvoir disposer des données nécessaires lors de l'inventaire. Un moyen complémentaire de simplifier l'inventaire est la constitution de bases de données secondaires intégrées à l'outil de saisie de l'inventaire et la détermination de valeurs moyennes pour les données auxquelles l'ACV se montre peu sensible. Pour les calculs d'émissions directes au champ faisant appel aux données météorologiques, dans le contexte français, le réseau de stations de Météo France offre une bonne couverture du territoire. Cependant, la disponibilité des données nécessite de disposer d'un droit d'accès ou d'un budget pour leur achat.

### 2.4 LA QUALITE DES RAISINS DANS L'ACV

L'approche proposée pour intégrer la performance qualitative de l'ITKv dans l'optimisation de l'éco-efficience des ITKv est originale et novatrice pour deux raisons : i) parce qu'elle fait appel à une notion non encore développée en viticulture à notre connaissance, celle du degré de correspondance à un objectif qualitatif visé ; ii) car la qualité des produits n'a encore jamais été intégrée dans les ACV viticoles et très rarement dans les ACV agricoles.

Il s'agit d'une première étape dans la prise en compte de la qualité du raisin dans l'ACV viticole. Utilisé comme unité fonctionnelle dans l'ACV, l'indicateur $Q_g$ a permis d'évaluer les impacts environnementaux liés à l'obtention d'un niveau qualitatif donné. Cependant, c'est couplé au rendement que $Q_g$ permet de prendre en compte la fonction première de l'itinéraire de production de raisins AOC, à savoir la production d'une quantité suffisante de raisins répondant à un objectif qualitatif donné. Il demeure que les deux valeurs $Q_g$ et le rendement de la parcelle sont tous deux très sensibles aux variations du climat voire à des évènements climatiques extrêmes (grêle, forte pluie) qui les modifient indépendamment de l'ITKv mis en œuvre. Une UF qui combine ces deux valeurs est donc doublement sensible aux aléas climatiques, elle doit donc être complétée par des UF moins sensibles à ces aléas comme l'ha de vigne cultivé. Leur utilisation renforce la nécessité de la prise en compte de plusieurs millésimes contrastés et caractérisés du point de vue climatique, et du point de vue des niveaux qualitatifs des raisins obtenus localement. Par ailleurs, du fait de la sensibilité importante du fonctionnement de la vigne et par conséquent de la composition des raisins aux caractéristiques du milieu (Coulon 2012; Morlat 2010), les variations de valeurs de $Q_g$ entre différentes parcelles ne peuvent être uniquement imputées à l'itinéraire, ce qui pourrait rendre délicate la comparaison d'ITKv de parcelles implantées dans différents milieux sur la base d'une UF qualitative, cependant, considérant que le vigneron adapte ses pratiques au milieu pour le valoriser au mieux, il nous semble que cette comparaison est réalisable. Il est ausis possible d'adapter la cible qualitative aux différents milieux en interaction avec les acteurs de la production.

La cible qualitative servant à la détermination de $Q_g$ peut, et doit, être ajustée au potentiel qualitatif maximal envisageable compte tenu des conditions du millésime, en concertation avec les acteurs en charge de l'itinéraire technique.

Les effets de seuil constatés sur l'indicateur $Q_g$ du fait d'une combinaison de variables discrètes limitent la capacité de discrimination de l'indicateur. En effet, pour les cinq ITKv, seules deux valeurs de $Q_g$ ont été obtenues. L'utilisation d'un système expert associé à la logique floue permettrait une progressivité des résultats supprimant ces effets de seuil.

L'intégration de la qualité dans l'ACV via l'indicateur $Q_g$ basé sur des mesures réelles à la vendange ne permet pas de réaliser de calcul d'éco-efficience « à priori » sur des scenarios d'amélioration d'ITKv ou de création d'ITKv innovants. Dans l'objectif d'optimisation environnementale des ITKv existants ou d'écoconception d'ITKv, il faut pouvoir prévoir l'effet d'un changement de pratique sur la qualité du raisin parallèlement à l'effet de ce changement sur les impacts environnementaux potentiels. Cet objectif d'optimisation conjointe qualité-environnement ne pourra être atteint qu'au moyen d'un modèle prédictif de la qualité du raisin en fonction des choix techniques et prenant en compte les facteurs du milieu (Beauchet et al. 2014b). Un tel modèle restituant les effets de phénomènes biologiques et physiques complexes et multiples est long et complexe à construire et n'a pu être abordé dans le cadre de cette thèse.

Le couplage ACV/qualité peut enfin être abordé sous un angle différent de celui de l'intégration de la qualité à l'unité fonctionnelle. Müller-Lindenlauf et al. (2010) pour le lait, l'ont considérée comme un impact en parallèle des autres issus de l'ACV. Une troisième voie à explorer est celle du couplage de l'ACV et de l'évaluation de la qualité par un outil d'analyse multicritères (Beauchet et al. 2014b) comme l'ont réalisé Mouron et al. (2012; 2013) pour l'arboriculture fruitière en joignant évaluations environnementale et économique.

# 3 PERSPECTIVES

## 3.1 LE DEFI DE LA PRISE EN COMPTE DES SPECIFICITES DE LA VITICULTURE BIOLOGIQUE DANS L'ACV

Deux ITKv conduits en agriculture biologique ont fait partie de cette étude. Leur évaluation a posé spécifiquement problème concernant la prise en compte des impacts de la protection phytosanitaire, comme souligné au § 2.2.1 du présent chapitre. Cette limite est aussi mentionnée par Alaphilippe et al (2014) pour la production de pommes biologique. De même, les résultats de FwEtoxP incluant le cuivre (calcul d'émissions issu des résultats de SALCA ETM) calculés par le modèle de caractérisation USETox$^{TM}$ doivent être considérés avec une extrême précaution, les modèles calculant le devenir des substances inorganiques dans USETox$^{TM}$ n'étant pas conçus pour ce type de substances. Les facteurs de caractérisation des inorganiques sont d'ailleurs classés comme provisoires dans la méthode, du fait de leur haut degré d'incertitude. La question des pesticides inorganiques n'est pas propre à la production biologique mais la concerne au premier chef puisque la quasi-totalité de sa protection antifongique repose sur de telles substances du fait qu'elle n'utilise pas les substances actives organiques chimiques xénobiotiques.

Les défis liés à la prise en charge des spécificités de l'agriculture biologique dans l'ACV dépassent la question des pesticides. Meier et al. (2015) mentionnent, notamment, la nécessaire amélioration de la prise en compte des spécificités des engrais et amendements organiques, et le rôle des pratiques dans les modèles d'émissions azotées et carbonées.

En viticulture, la question de la fumure organique n'est toutefois pas propre à l'agriculture biologique ; à titre d'exemple, tous les ITKv de la présente étude font appel à de la fumure organique. Les fertilisants et amendements d'origine organique sont encore effectivement, très peu représentés dans les bases de données secondaires d'ACV comme Ecoinvent (Nemecek and Kägi 2007). Ajuster au plus près la modélisation des impacts de leur fabrication demande alors de réaliser une investigation des processus de production pour chaque produit employé. Un seul type de processus de compostage est renseigné dans Ecoinvent, nous avons choisi, dans un premier temps, sans reconstituer en détail la chaine d'élaboration des différentes fumures organiques, d'adapter les processus existant dans Ecoinvent pour intégrer certaines spécificités de fabrication (séchage naturel ou artificiel) de chacun des engrais ou amendements organiques. Par manque de données, les variations d'émissions lors de différents types de compostage n'ont pu être ajustées. Les engrais organiques participant fortement à certains impacts comme l'eutrophisation, il est nécessaire de travailler à combler ces manques méthodologiques et de données. Une expertise scientifique collective en cours de finalisation à l'INRA avec le CNRS et l'IRSTEA sur la valorisation des matières fertilisantes d'origine résiduaires sur les sols agricoles devrait prochainement apporter des éléments utiles en ce sens.

## 3.2 ELARGIR LE CHAMP DES IMPACTS AUX SERVICES ECOSYSTEMIQUES

Le souhait de maximiser les services écosystémiques rendus par la viticulture, notamment au sein de la parcelle cultivée, est partagé entre l'agriculture biologique et intégrée. Il est exprimé en ACV dans les catégories d'impacts liées à l'occupation et au changement d'occupation des sols.

L'ACV ne remplit pas pleinement son rôle d'éviter les transferts d'impacts d'une catégorie à l'autre si les catégories importantes ne sont pas toutes représentées. Or à ce jour certains des impacts importants liés aux services écosystémiques ne sont pas pris en compte dans l'ACV en viticulture.

La restauration de la qualité et de la fertilité des sols est un objectif de la viticulture biologique, encore non pris en compte dans les ACV viticoles. Il sera donc utile de décliner, pour la viticulture, les indicateurs récemment développés en ACV agricole liés à la qualité des sols comme le tassement des sols, l'érosion et le contenu en matière organique des sols (Garrigues et al. 2013; Garrigues et al. 2012; Oberholzer et al. 2012). Ces catégories d'impacts présentent d'ailleurs aussi un intérêt important pour évaluer les productions conventionnelles.

L'enjeu fort à l'échelle planétaire de la préservation des écosystèmes, notamment en vue des services qu'ils peuvent rendre à l'humanité (Millennium-Ecosystem-Assessment 2005) se retrouve à l'échelle de la parcelle de vigne où une biodiversité importante permet une meilleure régulation des ravageurs (Duso et al. 2010; Veres et al. 2013) et où les pratiques sont des leviers efficaces (van Helden et al. 2012), même si la constitution du paysage environnant compte aussi beaucoup dans la présence de cette biodiversité utile (Veres et al. 2013). L'impact de l'agriculture sur l'évolution de la biodiversité peut être pris en compte dans l'ACV aujourd'hui, dans les impacts liés à l'occupation des sols et au changement d'occupation des sols, par des facteurs de caractérisation régionaux end-point basés sur un potentiel de variation de la biodiversité (nombre d'espèces vouées à l'extinction sur un espace donné (de Baan et al. 2013) ou richesse relative en espèces (Elshout et al. 2014)) causée par l'activité occupant le sol. Une liste d'activités inclut chaque type de culture ou d'état naturel de l'espace utilisé pour l'élaboration du produit. Pour la viticulture, trois types d'occupation de sol sont aujourd'hui disponibles dans les méthodes de caractérisation qui incluent une catégorie d'impact exprimant l'effet de l'occupation du sol sur les écosystèmes. Il s'agit de vigne, vigne intensive et vigne extensive, la plupart des méthodes affectent cependant le même facteur de caractérisation aux trois types, et certaines affectent un facteur inférieur à la vigne extensive. Antón et al.(2014) ont testé l'approche de caractérisation de l'impact de l'occupation des sols sur les écosystèmes proposé par de Baan et al (2013) pour deux systèmes agricoles d'intensité différentes, et arrivent à la conclusion que c'est un moyen intéressant d'évaluer l'impact des pratiques sur la biodiversité, mais que la finesse du grain doit être accru avec des facteurs de caractérisation plus spécifiques au site et plus spécifiques aux types de pratiques (ex : intensif, extensif, irrigué, serres, biologique). Un chantier conséquent est donc à ouvrir pour permettre de quantifier ces impacts à l'échelle parcellaire pour des itinéraires variés.

Enfin Le stockage du carbone dans le système sol-plantes (y compris couvert enherbé) d'un vignoble a été quantifié par Williams et al. (2011) à 87 Mg C/ha de vignoble (contre 125 Mg pour la forêt voisine). L'inclusion du stockage du carbone dans les calculs d'éco-efficience est un enjeu politique important pour la filière viticole, comme pour la plupart des filières de productions agricoles susceptibles de contribuer au stockage du carbone. Cet élément n'a pu être instruit dans le temps imparti pour cette thèse, mais doit être intégré dans les projets futurs visant à améliorer le cadre méthodologique proposé.

### 3.3 L'ACV DES ITINERAIRES TECHNIQUES VITICOLES COMME APPUI AU CONSEIL DE TERRAIN

La méthode de l'ACV apparaît, au travers de nos résultats, comme une méthode puissante d'évaluation et d'aide à l'amélioration des itinéraires techniques viticoles à l'échelle parcellaire. Elle implique toutefois dans sa forme complète une forte expertise pour sa mise en œuvre et son interprétation, et un long temps de constitution d'inventaire des flux. Son utilisation pour le choix des itinéraires techniques viticoles ne peut donc être une aide directe au pilotage quotidien. Son utilité réside à différents niveaux :

- Tout d'abord, le cadre méthodologique complet mis au point dans cette thèse permet, à l'échelle d'une région, d'une coopérative ou d'une AOC par exemple, de comprendre, sur la base d'une typologie de la diversité existante, comment se structure l'impact environnemental des ITKv en place pour envisager les voies d'améliorations principales pour chaque type d'ITKv ou l'effet qu'aurait un changement de technique dans un cahier des charges par exemple sur cet impact. C'est un moyen d'orienter le conseil à la parcelle, et les cahiers des charges techniques. Toutefois, la généralisation des résultats à différentes parcelles sans prise en compte des conditions spécifiques à chaque site n'est possible que pour les catégories d'impacts indépendantes du milieu, comme GWP 100a, POFP, Res, LC, et WU. Pour les catégories d'impact liées aux calculs d'émissions directes, comme AP, AEP-N, TEtoxP 100a ou FwEtox, un calcul des émissions directes aux conditions de chaque site sera nécessaire. On rejoint ici les questionnements liés à l'application de l'ACV à l'échelle du territoire (Loiseau et al. 2013; Pradeleix et al. 2012), qui dépassent les frontières de cette thèse, mais que celle-ci peut alimenter. En particulier, en négligeant les effets de bordure territoriaux, nous pourrions imaginer reconstruire des impacts territoriaux régionaux en combinant la diversité des impacts par type d'ITKv combinée à leurs surfaces régionales relatives, dans la mesure où l'on disposerait de cette dernière donnée. Ensuite, une prise en charge des évolutions de ces évaluations territoriales permettrait de disposer d'une image régionale des dynamiques d'impacts.

- Pour accompagner le conseil et la décision à la parcelle, la création de calculateurs simplifiés simulant la performance environnementale sur la base de l'ACV est une solution pertinente et déjà mise en œuvre dans plusieurs contextes agricoles comme l'élevage, la canne à sucre, ou les cultures sous serres (van der Werf et al. 2009; Renouf et al. 2013; Torrellas et al. 2013). Elle demande cependant de consentir à des simplifications afin d'alléger les phases d'inventaire et de calcul nécessaires à l'ACV, afin de permettre leur utilisation par les acteurs de terrain. Ceci restreint l'étendue des catégories d'impacts disponibles dans ces outils généralement au potentiel de réchauffement climatique, et des indicateurs de consommation de ressources comme l'eau et l'énergie. Il est essentiel que ces simplifications soient déterminées en interaction avec les futurs utilisateurs, afin de tenir compte de leurs priorités. C'est cette dernière démarche qui a été adoptée dans le projet Qualenvic piloté par le Groupe ESA et auquel ces travaux contribuent. La création d'un calculateur simplifié demandera de s'appuyer sur une base d'inventaire de processus unitaires de références pour chaque opération technique envisageable. L'enjeu sera de trouver le compromis idéal entre finesse du grain d'analyse, disponibilité des données, temps disponible pour sa conception puis pour les utilisateurs.

- Un autre moyen d'exploiter les potentialités de l'ACV pour le conseil de terrain est la mise à disposition de personnes compétentes en ACV dont la charge de travail serait assumée collectivement par plusieurs organismes

- L'ACV permet aussi la prise de conscience par les vignerons des impacts de leur production et des marges d'amélioration dont ils disposent. En particulier, voyant les différences d'éco-efficience des ITKv et des pratiques actuels, ils peuvent identifier leurs marges d'amélioration en utilisant des conduites déjà mises en œuvre par d'autres vignerons.

- C'est enfin un moyen d'alimenter l'évolution des cahiers des charges des démarches environnementales mises en place par les acteurs ou les instances gouvernementales (par exemple Terra vitis, Agriconfiance, HVE (Haute Valeur Environnementale)...)

## 3.4 SYSTEMES VITICOLES INNOVANTS, ACV ET ECO-CONCEPTION

Les processus d'amélioration des performances environnementales engagés au sein de la filière viticole relèvent à la fois de l'amélioration continue de l'existant et, pour atteindre des objectifs plus ambitieux, comme la réduction de 50% de la consommation des pesticides en 10 ans visée par le programme Ecophyto 2018 en France, relève de la conception de systèmes innovants (Lafond et al. 2013). Cette démarche, récemment mise en œuvre en viticulture, a abouti en France à l'installation de plateformes expérimentales mettant à l'essai des systèmes innovants à bas niveaux d'intrants phytosanitaires (Métral et al. 2012). Nos acquis permettraient de positionner ces ITKv dans la diversité actuelle, et de suivre progressivement les évolutions des ITKv pratiqués, signant ainsi une réelle évolution des pratiques viticoles. D'autre part, l'ACV pourrait apporter à ces comparaisons de systèmes une prise en compte de la dimension cycle de vie pour évaluer leurs impacts et ce sur un jeu de catégories d'impacts disponibles déjà large, comme nous l'avons vu.

Une approche complémentaire à celles déjà menées pour la conception de systèmes viticoles innovants dans un objectif d'amélioration des performances environnementales serait celle de l'écoconception basée sur l'ACV. L'écoconception est définie comme l'intégration des contraintes environnementales dans la conception et le développement de produits la conception d'un produit prenant en compte dès l'origine l'objectif de minimisation des impacts environnementaux, selon la norme ISO 14062 (AFNOR 2003), et ce tout au long de son cycle de vie (Le Pochat 2005). Toutefois l'exercice complexe de la conception de novo de systèmes agricoles basée sur l'ACV n'a pas encore été pratiqué en agriculture.

Dans le cadre de ces reconceptions de systèmes, comme souligné par Meynard (2012), les tensions entre les objectifs environnementaux peuvent exister (par exemple réduction des pesticides et consommation d'énergie). C'est ce que montrent ici les résultats d'éco-efficience des ITK1 et 5 notamment qui excellent dans une partie des catégories d'impact tout en montrant de piètres performances dans l'autre partie. L'ACV, par son approche holistique permet de mettre en évidence ces potentielles tensions. Toutefois, elle ne résout pas la question de la priorité à donner à l'un ou l'autre objectif environnemental pour le choix des systèmes innovants. Cette décision doit être le fait des acteurs de la filière selon les enjeux qui leur sont prioritaires, et dont l'ordre peut évoluer en fonction des contextes locaux ... ou planétaires.

# CHAPITRE 8 : CONCLUSION GENERALE

Cette thèse avait pour objectif d'évaluer dans quelles conditions l'ACV est une méthode appropriée à l'évaluation environnementale des itinéraires techniques viticoles de production de raisins de qualité à l'échelle parcellaire à des fins de choix des techniques.

Nos résultats ont permis à la fois de lever des verrous méthodologiques pour l'adaptation de l'ACV à l'évaluation des systèmes de production viticole en zone d'AOC et d'apporter des innovations méthodologiques.

Nous avons tout d'abord établi une chaine de traitement statistique originale permettant à partir d'enquêtes, de modéliser la diversité des itinéraires techniques d'une zone déterminée, afin de choisir, sur des critères précis, des cas représentatifs des types d'itinéraires existants. Cinq itinéraires techniques viticoles ont été ainsi choisis parmi ceux destinés à la production de vins blancs secs de Chenin AOC en Moyenne Vallée de la Loire.

La méthode de l'analyse du cycle de vie a été déclinée pour évaluer la viticulture de qualité à l'échelle parcellaire sur la base de ces cas, par l'établissement d'un cadre méthodologique spécifique comprenant : i) la définition de limites du système incluant les phases non productives et productives, ii) le choix des modèles disponibles les plus pertinents pour le calcul des émissions directes de polluants à la vigne, iii) l'adaptation fine du modèle d'émissions de pesticides organiques Pest LCI 2.0 aux spécificités viticoles, et l'augmentation de sa base de données de substances actives disponibles iv) la proposition et le test d'unités fonctionnelles basées sur un nouvel indicateur de qualité du raisin et permettant la prise en compte de la qualité dans les ACV de raisins destinés à la production de vins de qualité. Cet indicateur de qualité $Q_g$ exprime un degré de correspondance de la qualité mesurée à la vendange à un objectif qualitatif fondé sur une typologie du raisin établie à dires d'experts.

La méthode a permis de mettre en avant, à l'échelle parcellaire, des performances environnementales contrastées entre les itinéraires techniques évalués, d'identifier les pratiques responsables de ces contrastes, de proposer des solutions et d'en quantifier les effets. La généricité des résultats est différente selon les catégories d'impacts. Pour les catégories d'impact qui ne font pas appel à des calculs d'émissions directes conditionnées par le milieu, les résultats d'ACV peuvent être généralisés aux ITKv similaires aux cas étudiés, pour les autres impacts, il convient de recalculer les émissions pour chaque milieu ou d'identifier les gammes de variations des impacts à attendre de la diversité des milieux.

L'effet du millésime sur les résultats, testé ici sur un cas, mérite d'être pris en compte dans toute ACV viticole comme cela a été souligné dans d'autres contextes, viticole ou d'autres cultures pérennes, par plusieurs auteurs. Il s'agit au minimum de situer le climat de l'année étudiée dans la variabilité inter-annuelle, mais il est plus approprié de réaliser les calculs d'ACV sur plusieurs campagnes viticoles aux climats contrastés.

De nombreuses perspectives d'améliorations méthodologiques ont été dessinées pour plus de pertinence et de complétude des résultats d'ACV des ITKv, concernant les modèles d'émission directes, le recueil de données ou la prise en compte de la qualité dans l'ACV viticole. Les défis méthodologiques à relever pour une bonne prise en compte de la viticulture biologique par l'ACV ont été identifiés, ainsi que de nécessaires avancées à réaliser pour l'ACV viticole dans sa globalité pour la prise en compte des services ecosystémiques de la viticulture. Enfin les conditions de l'utilisation de l'ACV pour le conseil de terrain concernant le choix des techniques viticoles a été discuté.

Une autre perspective à ouvrir est celle de l'usage des méthodes conçues dans cette thèse. Qui et avec quelle compétence pourra mobiliser et utiliser les méthodes d'évaluation ainsi conçues ? Comment cet usage change les métiers de conseils, de développement dans un territoire donné ? Notre thèse n'a pu aller jusqu'à cette mise à l'épreuve des méthodes par des acteurs directement en charge de questions de développement de la viticulture, ce point sera à instruire dans diverses situations de développement. Un premier pas dans ce sens sera prochainement réalisé dans le cadre du projet Casdar Qualenvic que cette thèse contribue à alimenter, et qui explore « comment combiner qualité des produits alimentaires et performance environnementale (évaluée par ACV) » dans les filières laitière et viticole et inclut notamment des partenaires des chambres d'agriculture et des lycées viticoles.

Enfin, la place de ces méthodes dans l'enseignement agronomique viticole est à instruire. Comment les enseigner ? Comment rendre les étudiants, ou professionnels en formation permanente, aptes à les mobiliser dans leurs activités ? Dans le cadre du projet Casdar Qualenvic, des formations autour de l'ACV appliquée à la viticulture à destination d'élèves de formations viticoles supérieures (BTS et ingénieurs) et d'agents du développement seront proposées dès 2015, ceci constituera une première experience de transmission via l'enseignement. Ce second enjeu de mise en œuvre par un public de non chercheurs reste un défi pour les années qui viennent.

L'ensemble de ces éléments nous encourage à poursuivre l'amélioration et l'enrichissement de la méthode en même temps que la simplification de son application pour qu'elle puisse bénéficier aux viticulteurs et à leurs conseillers pour une amélioration des pratiques viticoles bénéfique à l'ensemble de la société.

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# 3 LISTE DES ABREVIATIONS

| Français | anglais | définition |
|---|---|---|
| ACV | LCA | analyse du cycle de vie |
| AICV | LCIA | analyse des impacts du cycle de vie |
| AOC | PDO | Appellation d'origine contrôlée |
| ICV | LCI | inventaire du cycle de vie |
| ITK | TMR | itinéraire technique |
| ITKv | | itinéraire technique viticole |
| | PAI. | substance active pesticide |
| UF | FU | unité fonctionnelle |
| catégories d'impact dans l'ACV | | |
| | ADP | potentiel de diminution des ressources abiotiques |
| | AP | potentiel d'acidification |
| | AEP-N | potentiel d'eutrophisation aquatique liée à l'Azote |
| | FwEtoxP | Ecotoxicité potentielle pour les organismes aquatiques d'eau douce |
| | GWP 100a | potentiel de réchauffement climatique à horizon 100 ans |
| | LC | utilisation d'espace |
| | OLDP | potentiel de diminution de la couche d'ozone |
| | POFP | potentiel de formation d'ozone photochimique |
| | POP | Potentiel d'oxydation photochimique |
| | TEtoxP 100a | potentiel d'écotoxicité terrestre à horizon 100 ans |
| | WU | utilisation d'eau douce |
| Substances | | |
| $C_2H_4$ | | Ethylène |
| CO | | Oxyde de carbone |
| COVNM | NMVOC | Composé Organique Volatil Non Méthanique |
| HC | | hydrocarbure |
| N | | Azote |
| $N_2O$ | | protoxyde d'azote |
| $NH_3$ | | ammoniac |
| $NO_3$- | | nitrate |
| $NO_x$ | | Les oxydes d'azote (dont NO et $NO_2$) |
| $P_2O_5$ | | pentoxyde de phosphore |
| $SO_2$ | | dioxyde de soufre |
| Unités | | |
| | CTUe | unité comparative pour les impacts d'écotocxicité aquatique d'eau douce = PAF × $m^3$ × jour par kg substance émise |
| | kg 1,4-DB eq | 1,4-équivalents dichlorobenzène /kg émission |
| | kg CFC-11 eq | kg équivalent Chloro fluoro carbone-11 / kg émission |
| | Kg $CO_2$ eq | kg dioxyde de carbone /kg émission |
| | kg Sb eq | kg équivalents antimoine/kg extraction |
| | kg $SO_2$ eq | kg équivalents dioxyde de soufre / kg émission |
| | PAF | fraction d'espèces potentiellement affectées |

# Thèse de Doctorat

Christel RENAUD-GENTIÉ

## Eco-efficience des itinéraires techniques viticoles : intérêts et adaptations de l'Analyse du Cycle de Vie pour la prise en compte des spécificités de la viticulture de qualité

## Eco-efficiency of vineyard technical management routes: interests and adaptations of Life Cycle Assessment to account for specificities of quality viticulture

### Résumé

Afin d'accompagner les acteurs des filières viticoles, notamment d'AOC, dans l'amélioration de l'éco-efficience de leurs produits, nous avons voulu identifier dans quelles conditions l'Analyse du Cycle de Vie est une méthode appropriée à l'évaluation environnementale des itinéraires techniques viticoles (ITKv) de production de raisins de qualité, à l'échelle parcellaire, afin de pouvoir choisir les opérations techniques et les ITKv les plus éco-efficients.

Un cadre méthodologique de l'ACV, adapté à cet objectif, a été établi et testé sur cinq ITKv réels et contrastés visant un même objectif qualitatif. Ces cas ont été choisis grâce à la mise au point d'une chaîne de traitement d'enquête originale, Typ-iti. Cinq groupes ont ainsi été identifiés et caractérisés parmi les ITKv de production de raisins de Chenin blanc pour vins blancs secs d'AOC en Moyenne Vallée de la Loire, dont trois en viticulture conventionnelle et deux en viticulture biologique.

Le cadre méthodologique ACV établi comprend : i) la définition du système étudié incluant les phases non productives et productives, ii) le choix des modèles disponibles les plus pertinents pour le calcul des émissions directes de polluants à la vigne, iii) l'adaptation fine du modèle d'émissions de pesticides organiques Pest LCI 2.0 aux spécificités viticoles, iv) la prise en compte de la qualité des raisins par deux unités fonctionnelles basées sur un indicateur de qualité du raisin original.

L'ACV apparaît comme une méthode complexe mais puissante pour le choix des ITKv, et utilisable à l'échelle parcellaire. Elle a révélé, i) des éco-efficiences contrastées pour les cinq ITKv contrastés, ii) les pratiques responsables de ces contrastes, iii) des solutions d'amélioration et leurs effets quantifiés sur les performances environnementales.

L'effet important du millésime sur les résultats, mis en évidence ici sur un cas, mérite d'être pris en compte dans toute ACV viticole.
De nombreuses perspectives d'améliorations méthodologiques sont discutées ici pour accroître la pertinence et la complétude des résultats ainsi que la généricité de la méthode et son accessibilité pour une application auprès d'acteurs du développement des filières viticoles.

**Mots clés**
**Environnement, vigne, ACV, Inventaire de Cycle de Vie, unité fonctionnelle, pratique, pesticide, émissions, typologie, échelle parcellaire, qualité, raisin, impact**

### Abstract

In order to contribute to the effort of eco-efficiency improvement of the wine sector, especially in the Protected Denomination of Origin (PDO) context, we worked to identify in which conditions Life Cycle Assessment (LCA) is an appropriate method for environmental assessment, at plot scale, of quality vineyard Technical Management Routes (TMRs), to permit the choice of the most eco-efficient technical operations and TMRs.

A methodological framework for LCA suited to this objective was designed and tested on five real and contrasted TMRs, oriented towards a same qualitative objective. These cases were chosen thanks to an original statistical analysis chain, Typ-iti, on the basis of a survey, among the TMRs producing Chenin blanc grapes for PDO dry white wines in the Middle Loire Valley. Five groups were identified and characterized, three in conventional viticulture, and two in organic viticulture.

The methodological framework that was established includes i) the studied system definition including productive and non-productive phases, ii) the choice of the most suitable and available models for calculation of pollutant direct emissions in the vineyard, iii) the customization of the organic pesticide emission calculation model, Pest LCI 2.0, to viticulture specific needs iv) the inclusion of grape quality in the LCA by two functional units including an original grape quality index.

LCA proves to be a method complex but powerful, usable at parcel scale for grape production TMRs choice. It revealed i) contrasted eco-efficiencies for the 5 contrasted TMRs, ii) the viticultural practices responsible for these contrasts, iii) solutions for eco-efficiency improvement and quantification of their eco-efficiency effects

The important effect of the production year on the results, highlighted here on one case, must be taken into account in any viticulture LCA. Numerous perspectives of methodological improvement are discussed here in order to increase relevance and completeness of the results as well as genericity of the method and its accessibility for viticulture development stakeholders.

**Key Words**
**Environment, vine, LCA, Life Cycle Inventory, Functional Unit, practice, pesticide, emissions, typology, plot scale, quality, grape, impact**

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