Università degli Studi della Tuscia di Viterbo

Dipartimento di Scienze Agrarie e Forestali

Corso di Dottorato di Ricerca in

Engineering for Energy and Environment
Curriculum "Biosystems and environment"
XXXII ciclo

VALORIZZAZIONE DI BIOMASSE RESIDUALI DEL SETTORE AGRICOLO

(s.s.d. AGR/09)

Tesi di dottorato di:
Dott. Vincenzo Alfano
Firma……………………

Coordinatore del corso
Prof. Danilo Monarca
Firma…………………......

Tutore
Prof. Danilo Monarca
Firma………..…………

Co-tutore
Dott. Luigi Pari
Firma……………………

A.A. 2019/2020

Riassunto

La ricerca di dottorato si inserisce in un contesto di transizione da modelli di economia lineare verso modelli di economia circolare, che prevedono il riutilizzo di sottoprodotti e scarti di produzione e dal contestuale sviluppo di diversi settori della bioeconomia che, in sostituzione di materie prime fossili, non rinnovabili, utilizzano risorse biologiche, nella produzione di svariati prodotti *biobased*, tra cui biomateriali, *biochemicals*, bioenergia ed alimenti.

La tesi ha avuto come oggetto l'analisi delle risorse di biomassa residuale del settore agricolo che risultano oggi scarsamente utilizzate, ma con un grosso potenziale sia in termini di disponibilità che di caratteristiche qualitative per molteplici destinazioni, e la valutazione sperimentale di tecniche di raccolta meccanizzata e di gestione logistica dei residui più promettenti, tra cui le potature, gli espianti di fine ciclo di vigneti e frutteti e i residui di trebbiatura.

La raccolta e la gestione logistica dei residui agricoli costituisce infatti una fase molto onerosa di una possibile filiera di valorizzazione, sia essa a scopo energetico o di bioraffineria, essendo questa tipologia di biomassa residuale caratterizzate da una bassa densità volumica e dispersione sul territorio. L'obbiettivo della tesi è stato quello di valutare le soluzioni meccaniche più innovative in grado di superare gli ostacoli legati alla fase di raccolta e logistica, che hanno, di fatto, frenato finora lo sviluppo di filiere basate sull'utilizzo dei residui agricoli.

La tesi è strutturata in una parte introduttiva, in cui si descrivono sintatticamente le attività realizzate nel corso del dottorato, con un rimando alle singole pubblicazioni originate da tali attività e presentate su riviste internazionali e in atti di convegno, allegate in appendice.

Nel primo capitolo si descrive il piano di attività e le finalità del progetto di dottorato. Il secondo capitolo è dedicato all'analisi del potenziale di biomasse residuali in Italia e alla presentazione di una nuova metodologia di stima sviluppata, in particolare, per le potature. Nei due capitoli successivi si descrivono, rispettivamente, le soluzioni meccaniche e logistiche finalizzate al recupero e trasporto, in un caso, delle potature ed espianti di fine ciclo e, nell'altro, dei residui di trebbiatura.

Per quanto riguarda le potature, si presenta una review delle macchine attualmente disponibili per la raccolta convenzionale e si descrive l'attività sperimentale finalizzata alla valutazione tecnico-economica di un cantiere innovativo per la raccolta, stoccaggio e pellettizzazione direttamente in campo delle potature di vite, con abbattimento dei costi di trasporto. Accanto alle potature, si evidenzia l'enorme potenziale degli espianti di vigneti e frutteti a fine ciclo produttivo, attraverso la descrizione delle attività di valutazione di un innovativo sradicatore, in grado di abbattere i tempi di lavoro, garantendo al contempo una adeguata pulizia delle radici dal terreno adeso, condizione essenziale per il successivo trasporto e stoccaggio ottimale.

Tra i residui di trebbiatura l'attenzione è stata posta sui tutoli del mais e sulla pula dei cereali. Il crescente interesse verso tali risorse, per finalità energetiche o zootecniche, ha spinto diverse aziende agro-meccaniche alla costruzione di dispositivi applicabili alle mietitrebbiatrici per una raccolta contestuale o successiva alla trebbiatura.

Per quanto riguarda i tutoli del mais è stata valutata una soluzione meccanica ideata da una ditta italiana in grado di operare il recupero dei tutoli contestualmente alla trebbiatura, senza compromettere le prestazioni di raccolta. Per quanto riguarda la pula dei cereali, dopo aver presentato lo stato dell'arte delle soluzioni meccaniche in correlazione alle finalità di recupero, tra le quali la riduzione del carico dei semi delle erbe infestanti, come accade in Australia, si descrive nel dettaglio la sperimentazione condotta in due stagioni successive di raccolta utilizzando una tecnologia sviluppata da una ditta francese in grado di realizzare la raccolta della pula in due modalità, separatamente dalla paglia o insieme ad essa durante l'imballatura.

Infine, si descrive una valutazione tecnico-economica finalizzata alla identificazione della distanza limite rispetto al centro di stoccaggio, di convenienza economica nella scelta tra due cantieri alternativi per la raccolta di paglia e stocchi, composti rispettivamente da carro auto-caricante e da imballatrice più forca e pianale e relative trattrici.

Abstract

The doctoral research was performed into a context characterized by the awareness of the need to adopt circular economy models, based on the re-use of residues and by-products replacing non-renewable fossil resources.

Availability assessment of agricultural residues currently not used introduces the experimental tests performed on mechanized collection systems for selected residues, such as pruning, end-of-cycle stumps and threshing residues.

The aim of the thesis was to evaluate the most innovative mechanical solutions able to overcome the obstacles linked to the collection and logistics. The harvesting and logistics of agricultural residues are the most expensive phases of a supply chain, both for energy and for biorefinery purposes. In fact, these types of biomass are characterized by low density and dispersion in the territory.

The thesis is structured in an introductory part, which describes the activities carried out during the doctorate, and a second part with the publications originated from such activities and submitted in international journals and in conference proceedings attached in the second part.

The first chapter describes the activity and the aims of the doctoral project. The second chapter is dedicated to the analysis of the potential of agricultural residues in Italy with a focus on a new estimation methodology developed for pruning. The two following chapters describe, respectively, the mechanical and logistic solutions aimed at recovering and transporting prunings and threshing residues.

Concerning the prunings, a review of the machines currently available for their collection is presented, such as the experimental activity aimed at the technical-economic evaluation of a mobile system for pelleting of vineyard pruning. In addition to pruning, the enormous potential of vineyards and orchards roots at the end of the life cycle is highlighted. An innovative root extractor able to reduce working times ensuring adequate root cleaning has been described.

Among the threshing residues the attention was placed on corn cobs and cereal chaff. The growing interest in these resources, for energy and zootechnical purposes, has led several

agro-mechanical companies to develop devices applicable to the combine harvesters for a contextual or subsequent recovery.

Concerning corn cobs, a mechanical solution designed by an Italian company able to perform the recovery of the cobs at the same time as threshing, without affecting the collection performance, was evaluated. As regards the cereal chaff, the state of the art of mechanical solutions in correlation to the recovery purposes, including the reduction of weed seeds, has been presented. Moreover, the test conducted in two successive harvesting seasons using a technology developed by a French company able to carry out the collection of the chaff separately or together with the straw is described in detail.

Finally, a technical-economic evaluation aimed at identifying the threshold distance from the storage centre, from which it is more economically convenient to gather the wheat and corn residues in bales instead of using a self-loading wagon.

Ringraziamenti

Un ringraziamento doveroso va al prof. Danilo Monarca, Coordinatore del corso di dottorato, per il prezioso supporto pur lasciandomi piena autonomia nell'attività di ricerca.

Ringrazio sentitamente il dott. Luigi Pari, tutor del presente dottorato e mio responsabile presso il CREA, per avermi affidato mezzi e responsabilità, consigliandomi e spronandomi continuamente all'attività di ricerca da svolgere.

Un ringraziamento assolutamente doveroso va a tutti i colleghi e amici del gruppo di lavoro coordinato dal dott. Pari, senza i quali non avrei potuto raggiungere i risultati ottenuti.

Sommario

1. Introduzione

Lo sviluppo della bioenergia negli ultimi anni è indirizzato verso l'utilizzo preponderante di biomasse residuali, sottoprodotti e scarti provenienti dai comparti agroforestali ed agroindustriali. In Italia, tale visione rinnovata della bioenergia si è concretizzata con la modifica del sistema incentivante che, a partire dal 2013, premia maggiormente gli impianti di piccola taglia ed alimentati con sottoprodotti (D.M. 6 Luglio 2012).

Le colture dedicate per la produzione di bioenergia, sono destinate preferibilmente ai soli terreni marginali con l'obbiettivo di evitare il dualismo, diretto e indiretto, nell'utilizzo dei terreni destinati alle produzioni alimentari (cambiamento indiretto dell'uso del suolo, ILUC-*Indirect land use change*) (EU 2015/1513, 2015). Inoltre, si stima che le sole colture dedicate non sarebbero comunque sufficienti per rispondere ai nuovi ed ambiziosi obiettivi del quadro UE per le politiche climatiche ed energetiche al 2030 (Stelte et al., 2012).

Il recente sviluppo della bioeconomia ha ampliato l'interesse per le biomasse non solo per finalità prettamente energetiche, ma verso i molteplici utilizzi delle industrie cosiddette *biobased*, quali la produzione di bio-materiali e biochemicals (Scarlat et al., 2015).

Per contrastare la crescente domanda di biomassa ed una possibile competizione per l'uso di una risorsa, rinnovabile ma non per questo inesauribile, la bioeconomia ha sposato alcuni elementi tipici dell'economia circolare, promuovendo il riutilizzo degli scarti e l'utilizzo in cascata della biomassa, nel rispetto della sua piramide del valore, preferendo tra gli utilizzi alternativi quelli finalizzati alla produzione di beni a più alto valore e per ultimo la produzione di energia (*Pharmaceutical and fine chemicals, food and feed, chemicals and materials, transportation fuels, power and heat*) (Kinne, 2003).

La sfida attuale, quindi, è quella di sfruttare in maniera sostenibile le biomasse disponibili, preferendo quelle finora scarsamente impiegate, come i residui agricoli, il cui utilizzo è ostacolato principalmente dalla convenienza economica della raccolta e della logistica di approvvigionamento (A. Dyjakon et al., 2014).

I residui agricoli, come le paglie e le potature, si caratterizzano, infatti, per una bassa densità energetica e per una elevata dispersione sul territorio, dovuta alla frammentazione aziendale, che ne hanno difatti limitato finora lo sfruttamento (Gebresenbet et al., 2018) (García-Galindo et al., 2016).

Una delle chiave di successo, è sicuramente rappresentata da una efficiente meccanizzazione delle operazioni di raccolta e movimentazione e la conseguente organizzazione ottimale delle fasi di trasporto e della logistica, che costituiscono infatti le voci di costo più onerose dell’intera filiera di approvvigionamento delle biomasse residuali (Liu, J., R. Grisso, 2013).

La fase di raccolta inoltre influenza fortemente la qualità del prodotto finale, requisito fondamentale per gli impianti di trasformazione. Nel caso delle potature, per esempio, la contaminazione di particelle di terreno è direttamente correlata alla regolazione del sistema pick-up della macchina raccoglitrice (Acampora et al., 2013).

Allo stesso modo la presenza di terra adesa sulle radici di frutteti e vigneti espiantati a fine ciclo colturale costituisce un ostacolo al loro conversione energetica. Oltre ad una serie di gravi problemi negli impianti, come corrosioni e incrostazioni, le ceneri sono anche responsabili della riduzione del potere calorifico della biomassa (Monti et al., 2008).

Per questo motivo molti costruttori di macchine hanno sviluppato attrezzature dedicate per la loro raccolta. Queste attrezzature sono già disponibili sul mercato e molti produttori offrono diversi modelli, specifici per le varie logistiche di raccolta.

Per altre tipologie di residui agricoli, come i tutoli del mais e la pula dei cereali, l’interesse è più recente, così come le attrezzature, spesso ancora nella fase prototipale.

La tesi di dottorato, attraverso l’analisi della disponibilità di biomasse residuali in Italia, una disamina delle tecnologie disponibili per la raccolta e logistica delle risorse più promettenti e la valutazione sperimentale di alcuni casi applicativi (recupero di potature di vite e produzione di agripellet, estrazione di espianti a fine ciclo di vita e stoccaggio, recupero e valorizzazione della pula dei cereali e tutoli del mais), intende offrire un quadro aggiornato dello stato dell’arte, evidenziare le potenzialità di risorse poco conosciute e contribuire alla nascita di nuove filiere *biobased*.

1.2 Obiettivi e piano di attività della tesi

Il progetto di dottorato ha avuto come obbiettivo la promozione dello sfruttamento di residui agricoli per finalità energetiche o come materie prime di nuove filiere biobased, attraverso l'identificazione delle risorse più promettenti e finora scarsamente utilizzate e la selezione delle soluzioni meccaniche e logistiche più efficienti per rendere economicamente vantaggiosa la loro raccolta, trasporto e trasformazione.

Il progetto si è articolato su tre linee di attività:

Linea 1 - Identificazione delle principali tipologie di residui colturali nel sistema agricolo italiano.

Linea 2 – Analisi delle soluzioni meccaniche e logistiche finalizzate al recupero e trasporto delle tipologie di biomasse residuali selezionate.

Linea 3 – Prove di raccolta meccanizzata e bilancio economico ed energetico per le risorse selezionate.

L'elaborato di tesi presenta nella prima parte una sintesi delle attività svolte e dei principali risultati conseguiti, riportando in appendice le pubblicazioni originate da tali attività e presentate su riviste internazionali e in atti di convegno.

1.3. Collaborazioni esterne e finanziamenti alle attività sperimentali

Il Dottorato di ricerca è stato svolto presso il Centro di ricerca Ingegneria e Trasformazioni agroalimentari del CREA di Monterotondo (RM), dove il dottorando è in servizio come ricercatore.

Le attività di ricerca oggetto della tesi di dottorato sono state coordinate dal dott. Pari nell'ambito del Progetto H2020 EUROPRUNING *"Development and implementation of a new and non existent logistics chain for biomass from pruning"* (http://www.europruning.eu/) e del Progetto H2020 AGROinLOG *"Demonstration of innovative integrated biomass logistics centres for the Agro-industry sector in Europe"* (http://agroinlog-h2020.eu/en/home/).

2. Disponibilità potenziale di residui agricoli in Italia

Negli ultimi anni numerosi studi hanno tentato di fornire delle stime, in Europa ed in Italia, della disponibilità di biomasse residuali dal settore agricolo. I loro risultati sono, però, spesso discordanti o non direttamente confrontabili a causa delle diverse finalità, scala territoriale e metodologia applicata. Come evidenziato dai progetti europei BEE[1] e CEUBIOM[2], il cui obiettivo era armonizzare e migliorare la coerenza, l'accuratezza e l'affidabilità delle stime di biomassa, queste utilizzano un'ampia gamma di approcci, metodologie, ipotesi e set di dati che portano a stime diverse del potenziale di biomassa (Vis & van den Berg, 2010).

Abbastanza diffuso è l'uso di indici di produzione di biomassa, solitamente espressi in termini di produzione di residui per ettaro, Residue to Surface Ratio - RSR o per unità di prodotto principale (ad esempio paglia/grano, potatura/frutta), Residue to Product Ratio - RPR. Recentemente due importanti studi su scala nazionale, basati sull'utilizzo di tali indici, hanno prodotto una stima aggiornata della disponibilità di biomasse residuali in Italia, con un livello di dettaglio provinciale. Si tratta del "Censimento del potenziale energetico nazionale delle biomasse" realizzato dall'ENEA (Motola et al., 2009), basato su gli indici RPR e quello realizzato dall'ENAMA[3] nel "Progetto Biomasse" dove si sono utilizzati agli indici RSR.

Coerentemente con la vocazione colturale regionale, i due studi sono stati concordi nell'attribuire una ripartizione analoga tra i residui delle colture erbacee e i residui delle colture arboree nelle macro aree Nord, Centro e Sud. Tuttavia, complessivamente, lo studio ENEA sovrastima del 30% la disponibilità dei residui arborei e del 40% la disponibilità dei residui erbacei (Tabella 1).

[1] BEE - Biomass Energy Europe (http://www.eu-bee.eu/)
[2] CEUBIOM - Classification of European Biomass Potential for Bioenergy Using Terrestrial and Earth Observations (http://www.ceubiom.org/)
[3] Ente Nazionale per la Meccanizzazione Agricola (www.progettobiomasse.it)

Tabella 1 – Disponibilità di residui da colture arboree ed erbacee negli studi realizzati da ENEA ed ENAMA

	Colture arboree		**Colture erbacee**	
	ENEA	**ENAMA**	**ENEA**	**ENAMA**
Anno/i di riferimento	2006	Media 2006-2009	2006	Media 2006-2009
Biomassa valutata	Potature + espianti	Potature	Paglie di cereali, stocchi del mais	Paglie di cereali, stocchi e i tutoli del mais, stocchi del girasole
Potenziale complessivo (kt/a s.s.)	4.906,4	3.446,2	15.710,9	9.356,5
Nord	*1.057,9 (22%)*	*614,4 (18%)*	*9.995,5 (64%)*	*6.291,8 (67%)*
Centro	*645,3 (13%)*	*535,1(16%)*	*2.130,2 (14%)*	*1.356,5 (15%)*
Sud	*3.203,3(65%)*	*2.204,2 (64%)*	*3.585,2 (22%)*	*1.708,1 (18%)*

2.1 Sviluppo di una nuova metodologia per il calcolo del potenziale di potature

Il limite degli indici utilizzati in queste stime deriva dal fatto che essi rappresentano una media di condizioni estremamente variabili, registrate empiricamente o ottenute da fonti bibliografiche e, quindi, la loro applicazione fornisce una stima approssimativa e non accurata del potenziale reale.

Nel caso delle potature, per esempio, la disponibilità potenziale è funzione di diversi fattori, che sono da un lato direttamente correlati alle caratteristiche della coltura, come specie, varietà ed età e, dall'altro, alle pratiche agronomiche, come forma d'allevamento, sesto di impianto, densità, metodi di potatura (tipo e intensità), regime di irrigazione, tipo di suolo e clima.

Per tenere conto di tali fattori, nell'ambito del Progetto EuroPruning è stata avviata una specifica attività di rilevamento, mediante analisi di letteratura, la somministrazione di questionari ad agricoltori e agronomi, la consultazione di banche dati agro-metereologiche (come il portale GAEZ, Global Agro-Ecological Zones della FAO). L'obiettivo è stato quello di ottenere modelli di regressione e, quindi, equazioni matematiche per poter prevedere la quantità di potatura in funzione dei fattori con le migliori correlazioni.

Sul sottoinsieme dei dati ottenuti per l'Italia, è stata effettuata un'analisi non parametrica per valutare il grado di correlazione tra gli aspetti selezionati (complessivamente 28) e la produzione di potatura (variabile dipendente). A tale scopo è stato utilizzato il coefficiente di correlazione di Spearman. Correlazioni moderate ($0.3< \rho<0.6$) sono state trovate soltanto per alcune variabili climatiche, per le quali è stato eseguito uno studio di regressione. In particolare, sono state definite due equazioni, valide rispettivamente per l'olivo e la vite, grazie alle quali è possibile predire la quantità di biomassa in funzione dell'*Ecocrop suitability index.*

I risultati, analizzati nel dettaglio nell'articolo in appendice, evidenziano enormi potenzialità, che tuttavia vanno analizzate tenendo conto anche di aspetti di carattere tecnico, economico ed ambientale, che riducono di fatto il potenziale in sottoinsiemi decrescenti di quello teorico (Figura 1).

Tra questi aspetti, l'efficienza dei sistemi di raccolta rappresenta l'elemento chiave per ampliare il più possibile il sottoinsieme rappresentato dal potenziale tecnicamente raccoglibile. La raccolta rappresenta la fase chiave dell'intera filiera agro-energetica, influenzando la qualità del prodotto ottenuto e le soluzioni logistiche che seguono fino al suo utilizzo, e di conseguenza la sostenibilità economica ed ambientale complessiva della filiera.

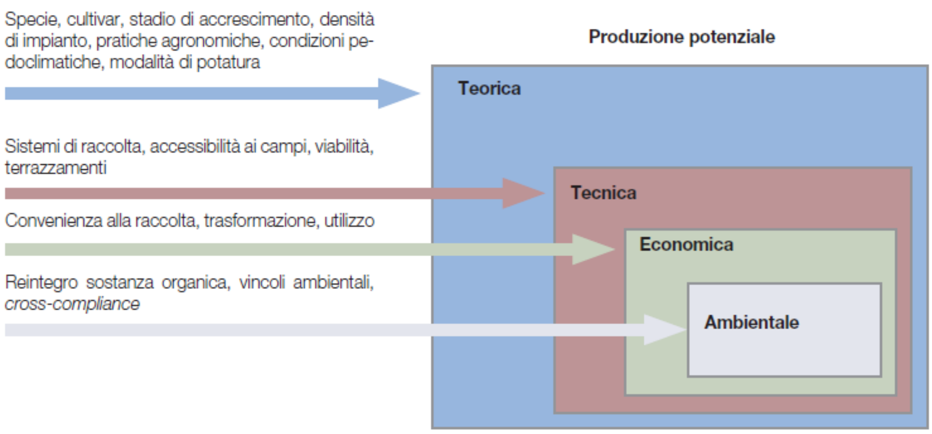


Figura 1 - Rappresentazione schematica dei diversi livelli del potenziale di biomasse residuali

L'attività ed i risultati ottenuti sono descritti dettagliatamente nella pubblicazione riportata in appendice:

Pari L., Alfano V., Garcia-Galindo D., Suardi A., Santangelo E. (2018). Pruning Biomass Potential in Italy Related to Crop Characteristics, Agricultural Practices and Agro-Climatic Conditions. Energies. 2018; 11(6):1365

3. Soluzioni meccaniche e logistiche finalizzate al recupero e trasporto delle potature e degli espianti di fine ciclo

3.1 Macchine per la raccolta delle potature.

Tra i residui colturali, le potature sono una risorsa importante per la produzione di bioenergia sia per la loro ampia disponibilità, sia per la qualità della biomassa ai fini energetici (contenuto di ceneri, potere calorifico e composizione chimica) (Picchi et al., 2018). In Europa sono disponibili annualmente oltre 13 milioni di tonnellate (su base secca) di biomassa da potatura dalle principali colture permanenti (oliveti, vigneti e frutteti); la maggior parte (circa l'80%) si trova nell'area del Mediterraneo, in particolare in Italia e Spagna (Arkadiusz Dyjakon & García-Galindo, 2019).

Tuttavia, l’uso razionale di questa fonte di biomassa è ostacolato da varie barriere legate alle fasi di raccolta delle potature e allo sviluppo di una filiera logistica sostenibile per la produzione di energia (Gebresenbet et al., 2018). Le potature prodotte annualmente dalle colture arboree sono ad oggi considerati più un problema che un’opportunità. Infatti, la maggior parte delle volte queste sono smaltite in modo scorretto attraverso la combustione diretta in campo che risulta impattante sia per l’ambiente che per la salute umana, con costi significativi (Picchi et al., 2018)(Spinelli et al., 2012).

La formulazione di normative più severe in materia di smaltimento delle potature nella maggior parte dei paesi europei ha portato ad un rinnovato interesse sulla raccolta di questa risorsa inutilizzata. La raccolta è una fase fondamentale che influenza la qualità del prodotto, il tipo di catena logistica e la sostenibilità economica della filiera energetica. Per questo motivo molti costruttori di macchine hanno investito nello sviluppo di attrezzature specifiche per il recupero delle potature ed oggi diversi modelli sono disponibili sul mercato adatti alle diverse filiere di approvvigionamento. La tipologia più diffusa è rappresentata dalle trinciatrici per sarmenti, mentre meno presenti sul mercato sono le cippatrici e le imballatrici. Uno studio condotto nell’ambito del Progetto Europruning, ha annoverato complessivamente 75 modelli di macchine disponibili sul mercato europeo, di cui 60 derivano dalla modifica di trincia convenzionali. Il 78% dei modelli presi in considerazione è costruito in Spagna ed in Italia, dove del resto vi sono le superfici di frutteti più estese.

Le trinciasarmenti derivano dalle trincia convenzionali, in cui il prodotto non viene rilasciato a terra, ma proiettato per mezzo di un tubo lanciatore orientabile (a collo d'oca) su un rimorchio o direttamente in un cassone integrato o in big-bag. Rispetto alle trinciatrici convenzionali presentano un sistema di pick-up più efficiente (numero dei denti). Le potature sono spezzate per mezzo dell'apparato di taglio, costituito da un rotore orizzontale collegato alla PTO del trattore, su cui sono montati un numero variabile di elementi appuntiti (mazze o martelli), o lame affilate (coltelli). Generalmente sono montati posteriormente (trainati o portati) al trattore con potenza da 50 a 70 kW.

Le cippatrici, rispetto alle trinciasarmenti, sono di più recente introduzione sul mercato, e sono presenti con un numero limitato di modelli (l'indagine citata ne ha rilevato 5). Si differenziano in base all'organo di cippatura, per numero e forma dei coltelli. È cruciale che il sistema di pick-up sia progettato accuratamente per evitare l'introduzione di sassi e terra ed il contatto con le lame, la cui usura o danneggiamento compromette la qualità del cippato. Il taglio netto e senza sfibrature del cippato garantisce una migliore conservabilità durante lo stoccaggio e l'omogeneità della pezzatura consente un più agevole impiego nei sistemi di convogliamento e alimentazione di caldaie, silos e tramogge.

Le imballatrici concettualmente derivano dalle imballatrici da foraggio convenzionali. L'imballatura presenta il vantaggio di una più agevole conservabilità del prodotto imballato che può durare anche diversi mesi, al termine del quale tuttavia si rende necessario il passaggio aggiuntivo di cippatura. Attualmente le imballatrici sono principalmente utilizzate per la raccolta dei sarmenti di vite, che risultano più facilmente processabili. Sono presenti sul mercato diverse mini rotoimballatrici (balle da 30 kg), adatte a lavorare tra i filari dei vigneti. Negli ultimi anni sono entrate sul mercato anche rotoimballatrici standard (balle 120x120 cm).

L'analisi dettagliata delle tecnologie esistenti e delle possibili filiere logistiche per la raccolta delle potature sono descritte nella pubblicazione riportata in appendice:

L. Pari, A. Suardi, E. Santangelo, D. García-Galindo, A. Scarfone, V. Alfano (2017). Current and innovative technologies for pruning harvesting: A review. Biomass and Bioenergy 107, pp. 398-410

3.2 Produzione di agripellet dalle potature di vite con cantiere mobile

La pellettizzazione rappresenta un'interessante soluzione in grado di superare gli ostacoli di carattere tecnico che hanno limitato finora l'utilizzo diretto dei residui di potatura (bassa massa volumica e densità energetica, disomogeneità, disponibilità stagionale) in piccoli impianti termici. L'agripellet, cioè pellet ottenuto da residui agricoli, presenta infatti caratteristiche non molto diverse dal pellet ottenuto dalle biomasse forestali, con analoghi vantaggi, quali elevata massa volumica e densità energetica, bassa umidità, alta omogeneità. Dal punto di vista energetico il pellet prodotto dai residui di potatura non si differenzia da quello derivante da legno di piante forestali. Tuttavia, esso presenta un maggior contenuto di azoto, cloro e ceneri, quest'ultime fortemente condizionate dalla terra e inerti sollevati assieme alla potatura dalla macchina raccoglitrice.

Pertanto, è stata analizzata la filiera di produzione di agripellet proposta dalla ditta Costruzioni Nazzareno, attraverso la valutazione tecnico economica, in due momenti distinti, degli elementi che la compongono: la trincia-caricatrice per potature (MAREV Alba 150) ed il cantiere mobile di pellettizzazione.

L'organo di taglio della raccoglitrice opera un taglio netto delle potature che possono essere stoccate in cumuli all'aperto per permettere una essicazione naturale contenendo i fenomeni fermentativi, prima della trasformazione in pellet. L'impianto mobile, trasportato direttamente in campo abbatte i costi legati alla logistica.

La biomassa è stata caratterizzata prima e dopo lo stoccaggio (avvenuto dopo 8 mesi) e dopo la fase di pellettizzazione. Sono state valutate le prestazioni, il consumo di carburante e la qualità del lavoro della raccoglitrice, insieme alla produttività e al consumo di energia del sistema mobile di pellettizzazione. Sono stati stimati i costi di produzione del pellet in tutte le fasi della filiera, considerando due scenari. Stoccaggio e pellettizzazione direttamente in azienda o in un luogo dedicato a distanza variabile dai campi. Come confronto è stata considerata la produzione e utilizzo diretto di cippato.

I risultati indicano che le prestazioni della raccoglitrice sono comparabili con quelle delle soluzioni commerciali; il cippato ha mostrato eccellente comportamento durante lo stoccaggio, consentendo la diretta pellettizzazione senza essiccazione forzata; la qualità del pellet buona e paragonabile a quella prodotta da biomassa forestale. Dal punto di vista economico, la pallettizzazione in campo ha evidenziato buoni margini di profitto rispetto al valore di mercato del pellet di categoria A2, utilizzato come riferimento. Tale margine si riduce gradualmente e si annulla in media a 50 km di distanza dai campi, quando si rende necessario il trasporto ad un centro di stoccaggio intermedio.

L'attività ed i risultati ottenuti sono presentati in maniera esaustiva nella pubblicazione riportata in appendice:

Toscano G., Alfano V., Scarfone A., Pari L. (2018). Pelleting Vineyard Pruning at Low Cost with a Mobile Technology. Energies. 2018; 11(9):2477.

3.3 Raccolta e stoccaggio degli espianti a fine ciclo colturale

L'eliminazione delle ceppaie dei frutteti a fine ciclo di vita è una pratica necessaria per rendere il terreno nuovamente disponibile al successivo ciclo colturale. Generalmente viene praticata la trinciatura delle radici nel suolo seguita dall'aratura, con tempi e costi di lavorazione elevati e con il pericolo del propagarsi di virosi radicali. In alternativa, le ceppaie vengono estratte con escavatori e inviate in discarica o stoccate e cippate per essere utilizzate come biomassa combustibile, ma con un basso valore energetico per l'elevata presenza di terra.

Recentemente è stato offerto sul mercato un innovativo sistema di estrazione in grado di ridurre i tempi di lavorazione e offrire un prodotto relativamente pulito. La macchina sviluppata dalla ditta Gottardo, concepita per l'estrazione delle radici dei vigneti ben si adatta anche ad altri frutteti intensivi a filare (Picchi G., 2012).

È un'attrezzatura portata al sollevatore posteriore di trattici di media portanza, che in un unico passaggio estrae rapidamente le ceppaie e le dispone lungo la fila, pulendole al contempo dalla terra. Il telaio robusto solleva le radici grazie a 3 aste unite da un coltello, costituito da due erpici paralleli, distanziati tra loro di 1 metro e uniti da una lama basale.

Figura 2 - Sradicatore Gottardo SR 500 HT. Estrazione radici di vite

Con il semplice avanzamento del trattore questi tre elementi compiono il taglio delle radici, isolando le ceppaie in una sezione di terreno di larghezza fissa e per una profondità massima di 75 cm. Sulla lama orizzontale si trovano incernierate 3 barre che nella loro corsa poggiano su un secondo asse orizzontale fuori terra dotato di denti ricurvi. Questo asse ha una sezione asimmetrica ed è messo in rotazione da due motori idraulici, causando un moto alternativo nelle barre. L'intera struttura che sostiene l'asse può essere basculante per azione di un martinetto idraulico, variando l'inclinazione durante il lavoro. La funzione delle barre inclinate e dell'intera struttura è quella di spingere le ceppaie fuori dal terreno agitandole vigorosamente per favorirne così il distacco della terra prima di essere espulse posteriormente.

Nell'ambito del Dottorato è stata realizzata un'attività sperimentale finalizzata a valutare l'efficienza dello sradicatore descritto per il recupero di ceppaie di vite, ed il comportamento delle stesse durante la fase di stoccaggio ai fini di un utilizzo per scopi energetici.

L'attività ed i risultati ottenuti sono presentati in maniera esaustiva nella pubblicazione riportata in appendice:

Pari L., Scarfone A., Alfano V., Bergonzoli S., Gallucci F., Santangelo E. (2017). Testing open-air storage of stumps to provide clean biomass for energy production. Energies 10(11),1725

4. Soluzioni meccaniche e logistiche finalizzate al recupero e trasporto dei residui di trebbiatura

L'interesse per la possibile valorizzazione dei residui di trebbiatura ha spinto negli ultimi anni diverse aziende agro-meccaniche a ideare soluzioni per il loro recupero. Concettualmente, queste prevedono la raccolta dei residui separatamente dalla paglia o insieme ad essa durante l'imballatura.

4.1 Review delle macchine per la raccolta della pula dei cereali

Tra i residui di trebbiatura, la pula dei cereali è oggetto di un crescente interesse dettato sia dai potenziali utilizzi, che dalla elevata disponibilità (McCartney et al., 2006).

La pula è il sottoprodotto che si origina durante la trebbiatura nella fase di pulizia del grano ed è composta da glume, scafi, reste, paglia sminuzzata, semi danneggiati e semi di erbe infestanti. Durante la trebbiatura, la pula insieme agli altri residui fini trattenuti dai crivelli viene soffiata sul retro della mietitrebbia. Questo materiale viene normalmente lasciato cadere sul terreno sotto l'andana di paglia dove non può essere raccolto dal pick-up nella successiva operazione di imballatura.

Si stima che tale frazione costituisca circa il 7% del prodotto trebbiato (il 40% è costituito dai semi, il 48% dalla paglia, il 5% dalle stoppie) e, pertanto, più di 50 Mt sono disponibili ogni anno in Europa. L'interesse è orientato verso gli utilizzi energetici, in combustione insieme alla paglia o separatamente dopo pellettizzazione (Weiß & Glasner, 2018) o nei processi di produzione di bioetanolo di seconda generazione (Zhang et al., 2018). Nonostante abbia un basso valore nutritivo, data la disponibilità, la pula costituisce una importante risorsa integrativa nell'alimentazione zootecnica (McCartney et al., 2006) e una buona alternativa al fieno nell'alimentazione invernale (Mann et al., 1988).

Inoltre, dal punto di vista agronomico, la raccolta della pula durante la trebbiatura può ridurre lo stock di semi di erbe infestanti rimuovendoli prima che vengano restituiti al campo (Shirtliffe & Entz, 2005) (Walsh et al., 2013).

Attualmente sono disponibili alcune soluzioni commerciali ed altre sono in fase prototipale. Concettualmente, esse si basano su due modalità di gestione:

- raccolta della pula insieme alla paglia;

- raccolta della pula separatamente da essa.

Nel primo caso, la pula viene scaricata sopra l'andana o al suo interno per essere recuperata, in un secondo momento, da una imballatrice insieme alla paglia, aumentando del 20-25% la biomassa totale raccolta.

Nella raccolta separata, la pula viene inviata ad un sistema di raccolta dedicato, che può essere un carrello trainato da un trattore o dalla stessa mietitrebbia, un container integrato nella parte posteriore della mietitrebbia o una imballatrice non-stop.

Un'analisi delle soluzioni disponibili ha evidenziato la presenza di:

1. Sistemi andanatori
2. Sistemi a turbina
3. Sistemi con nastro trasportatore e carrello trainato ("chaff cart")
4. Sistemi con container integrati alla mietitrebbia
5. Sistemi di imballatura in continuo
6. Sistemi con spargipula modificati

La review è stata presentata dal dottorando con una presentazione orale alla European Biomass Conference 2018 ed i dettagli sono disponili nell'articolo riportato in appendice:

L. Pari, V. Alfano, A. Scarfone, S. Bergonzoli, A. Suardi, S. Lazar (2018). Best available technologies to harvest cereal chaff. Oral presentation, European Biomass Conference and Exhibition Proceedings 2018(26thEUBCE), pp. 77-82

4.2 Raccolta della pula con sistema a turbina Thievin

Tra le soluzioni individuate, nel 2018 e nel 2019 è stato testato con prove sperimentali di pieno campo il sistema a turbina commercializzato dalla ditta francese Thievin.

Il sistema è costituito da una tramoggia, collocata sotto lo scarico della mietitrebbia, che riceve la pula insieme agli altri residui fini di trebbiatura trattenuti dai crivelli (reste, paglia sminuzzata, semi danneggiati, semi di infestanti, ecc.). All'interno della tramoggia è alloggiata orizzontalmente una coclea che trasportata il prodotto verso una turbina che, azionata da un motore idraulico, ha la funzione di generare un flusso d’aria per il trasporto del residuo.

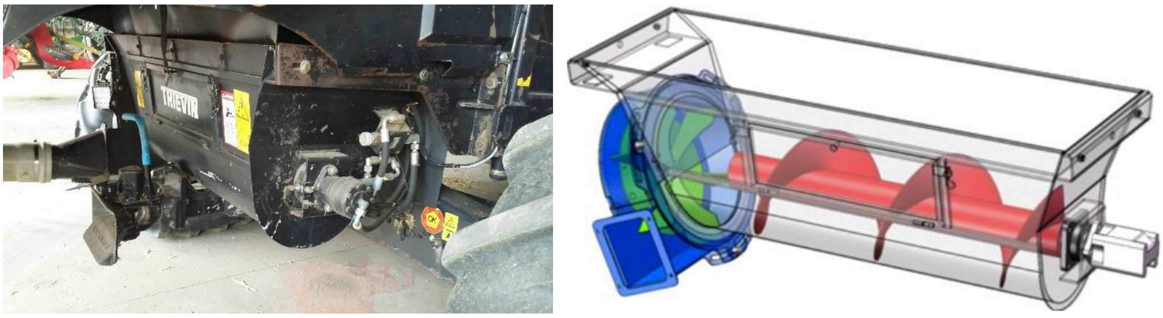


Figura 3 - Sistema a turbina e rappresentazione schematica

La pula può essere scaricata sopra l’andana per essere poi imballata in un secondo momento insieme alla paglia o, attraverso l’applicazione di un tubo in PVC, può essere scaricata su rimorchio dedicato per la raccolta separata. Qualora non si voglia raccogliere la pula ma integrarla nel terreno, il tubo in PVC viene rimosso dalla turbina e sostituito da un diffusore a forma di “V”. In questo caso, la pula proiettata ad alta velocità contro il diffusore viene dispersa in modo uniforme su ambo i lati.

A B C

Figura 4 – Modalità di lavoro del sistema Thievin: A) scarico della pula sull’andana; B) modalità dispersione; C) scarico su rimorchio

Le prove realizzate a luglio 2018 e a luglio 2019 a Nantes, in Francia, avevano l’obbiettivo principale di quantificare la pula raccoglibile, le prestazioni della mietitrebbia e della imballatrice nelle tre condizioni di lavoro (tesi):

- A: trebbiatura con scarico della pula sull'andana
- B: trebbiatura con spargimento della pula
- C: raccolta separata della pula su rimorchio (solo nel 2019)

In entrambi gli anni si è lavorato sullo stesso campo, su superficie da di circa 4 ettari. Questa è stata divisa in tre blocchi di uguali dimensioni e, a ciascun blocco è stata assegnata in modo casuale una ripetizione delle tesi a confronto. Per ogni trattamento e replica sono stati analizzati i tempi di lavoro, i consumi, la biomassa raccolta e le perdite di prodotto non raccolto.

Prima della trebbiatura è stata valutata la quantità di biomassa raccoglibile (paglia + spighe), pesando il materiale presente in 10 plot di $1m^2$. Le spighe sono state prelevate per la stima in laboratorio della granella con mietitrebbia da banco.

Tra i risultati più significativi si è potuto osservare che le prestazioni della mietitrebbia non sono state influenzate dal cantiere di raccolta e la pula imballata con il sistema A è stata in media nei due anni di 1,79 t/ha (pari ad un incremento del 30% e del 50% della biomassa imballata). Il cantiere C, con scarico della pula su rimorchio, ho consentito il recupero di 1,27 t/ha, evidenziando una inefficienza rispetto al cantiere A, seppur non statisticamente significativa.

L'attività ed i risultati ottenuti sono descritti nell'articolo sottomesso per la pubblicazione sulla rivista Energies:

Suardi A. Stefanoni W., Alfano, V., Bergonzoli, S., Pari, L. (2019). Equipping a combine harvester with turbine technology increases the recovery of residual biomass from cereal crops via the collection of chaff. Energies 2020, 13, 1572.

4.3 Raccolta dei tutoli del mais con sistema "Harcob"

I tutoli del mais costituiscono una risorsa molto interessante con una vasta gamma di applicazioni, tra cui la produzione di materiale assorbente per lettiera animale, materiale abrasivo per il trattamento delle superfici di metallo o legno, adsorbente per la produzione di carbone attivo per il trattamento delle acque, o, anche, substrato per la coltivazione idroponica. A scopo energetico, presenta un elevato potenziale metanigeno (250 Nm^3 CH_4/t s.v) negli impianti per la produzione di biogas. A fronte di una produzione media di circa 15 t/ha di granella, è attesa una raccolta potenziale di 3 t/ha di tutolo (42% di umidità).

Finora l'impiego del tutolo era vincolato all'uso delle ormai obsolete spannocchiatrici. La ditta Agricinque Gruppo-Racca sita a Marene (CN), ha ideato il sistema "Harcob" che viene montato su mietitrebbiatrici a flusso assiale CASE IH (con omologazione e certificazione CE). Il sistema, consente di raccogliere e sminuzzare i tutoli di mais contemporaneamente alla granella e stoccarli in un cassone dedicato. La capacità di carico del cassone dedicato da 9 m3 (1.200-1.500 kg) corrisponde alla capacità di carico della granella. È possibile, quindi, effettuare contemporaneamente lo scarico dei due prodotti (con coclea dedicata), sia con la macchina ferma, che in movimento durante la trebbiatura, senza compromettere la produttività della mietitrebbiatrice.

Figura 5 - Mietitrebbia equipaggiata con il sistema "Harcob" per il recupero dei tutoli

A settembre 2017 è stata realizzata una prova sperimentale presso l'azienda agricola Giletta sita a Revello (CN), con lo scopo di valutare le prestazioni e la qualità del lavoro di una mietitrebbiatrice equipaggiata con il sistema "Harcob". Le prove di raccolta sono state effettuate su tre porzioni di campo adiacenti, in cui era coltivata la stessa varietà di mais. All'interno di ogni campo sono state individuate delle aree di forma rettangolare, di circa 2 ha ciascuna, dove sono state eseguite le prove sperimentali. In ogni parcellone sperimentale sono stati selezionati dieci plot di campionamento (repliche) di 1 m2 per la valutazione delle caratteristiche biometriche e produttive della coltura (numero e peso delle piante, diametro del fusto a livello del suolo, altezza delle piante). Campioni di biomassa (tutoli, granella, stocchi e foglie) sono stati prelevati e confezionati sottovuoto per la determinazione in laboratorio del contenuto di umidità. Direttamente in campo è stata misurata la massa volumica del tutolo di mais rispettando lo standard tecnico di riferimento.

Durante la raccolta sono stati misurati i tempi di lavoro per la valutazione delle prestazioni della mietitrebbia secondo la metodologia del CIOSTA (Comité International d'Organisation Scientifique du Travail en Agriculture) e le raccomandazioni della Società Italiana di Ingegneria Agraria (A.I.I.A.). Sono state infine analizzate le perdite di tutoli (%) non raccolti su cinque plot per ogni campo sperimentale.

Dalle prove condotte è stato messo in luce che il sistema Harcob, ha raccolto in media 2 t ha^{-1} di tutoli, con una produttività oraria di 4,1 t h^{-1}. Le perdite di tutoli sono state inferiori al 20%, evidenziando il corretto funzionamento del sistema. Il sistema Harcob ha operato senza alcun problema, non influendo sui tempi di raccolta della raccoglitrice.

Maggiori approfondimenti sono riportati nell'articolo riportato in appendice:

L. Pari, S. Bergonzoli, A. Suardi, V. Alfano, A. Scarfone, S. Lazar (2018). Maize cob harvesting: first assessment of an innovative system. Poster presentation, European Biomass Conference and Exhibition Proceedings 2018(26thEUBCE), pp. 323-325

4.4 Valutazione della logistica dei cantieri di raccolta e trasporto della paglia e degli stocchi di mais

Sono stati confrontati due differenti cantieri per la raccolta dei residui di trebbiatura (paglia e degli stocchi) valutando le prestazioni e i costi di tutte le macchine utilizzate: rotoimballatrice con trattrice, trattrice con forca e trattrice con pianale nel primo cantiere, carro auto-caricante nel secondo. Lo scopo era quello di individuare la distanza massima tra il campo ed il centro di stoccaggio entro cui risulta economicamente conveniente raccogliere la biomassa imballata (primo cantiere) rispetto alla forma sfusa (secondo cantiere).

	Cantiere A			**Cantiere B**
Fase operativa	Raccolta	Movimentazione	Trasporto	"Tutto in uno"
Motrice	Trattrice New Holland T6050	Trattrice John Deere 6420	Trattrice John Deere 6420	Trattrice New Holland T6050
Operatrice	Imballatrice New Holland BB940	Forca	Pianale	Carro auto caricante Elefant P31L
				

Figura 6 – Cantieri e macchine utilizzate nelle diverse fasi di raccolta dei residui di trebbiatura

Lo stesso protocollo sperimentale e le stesse macchine sono state utilizzate sia per la raccolta della paglia che per la raccolta degli stocchi del mais. È stato utilizzato un disegno sperimentale split plot, dividendo la superficie di lavoro in tre blocchi di uguali dimensioni assegnando a ciascun blocco in modo casuale una ripetizione di entrambe le tesi a confronto (imballatura, auto-caricamento). Per ogni trattamento e ripetizione, le prestazioni di tutte le macchine coinvolte sono state valutate attraverso lo studio dei tempi di lavoro e la valutazione dei consumi di carburante. Campioni di biomassa sono stati prelevati per la determinazione dell'umidità e del contenuto in ceneri. Successivamente al passaggio delle macchine si è provveduto a determinare le perdite di raccolta pesando la paglia rimasta a terra all'interno di 3 plots di 10 m2, individuati a caso sulla superficie di ciascuna ripetizione delle due tesi a confronto. Tutta la biomassa raccolta, in forma sfusa o imballata, è stata pesata utilizzando la pesa aziendale. Inoltre, 10 balle ottenute durante ogni ripetizione sono state pesate singolarmente, direttamente in campo con dinamometro digitale da 1000 kg, per la determinazione della densità apparente.

Il costo orario di tutte le macchine coinvolte è stato calcolato, analizzando i principali parametri tecnici ed economici: prezzo di acquisto, valore residuo, vita utile, interessi sul capitale investito, costi di riparazione, manutenzione e consumi. Ove possibile, queste informazioni state ottenute mediante interviste con i proprietari delle macchine, registrate direttamente durante le prove sul campo o integrate con i valori standard tabellati.

Utilizzando i costi orari desunti dal conto economico, la *bulk density* della biomassa, la capacità di carico e la velocità di trasporto media, sono stati calcolati i costi unitari di trasporto, per tonnellata di biomassa e chilometro percorso.

Si è potuto verificare che la distanza di circa 10 km e quella di16 km costituiscono il limite superato il quale l'utilizzo del cantiere A (imballatrice) risulta meno costoso del cantiere B (carro auto-caricante), rispettivamente per il trasporto della paglia e degli stocchi.

Un'analisi dettagliata dell'attività e dei risultati è presentata nella pubblicazione riportata in appendice:

Suardi, A., Bergonzoli, S., Alfano, V., Scarfone, A., Pari, L. (2019). Economic distance to gather agricultural residues from the field to the integrated biomass logistic centre: A Spanish case-study. Energies 12(16),3086

5. Bibliografia

Acampora, A., Croce, S., Assirelli, A., Del Giudice, A., Spinelli, R., Suardi, A., & Pari, L. (2013). Product contamination and harvesting losses from mechanized recovery of olive tree pruning residues for energy use. *Renewable Energy*. https://doi.org/10.1016/j.renene.2012.12.009

Dyjakon, A., Bukowski, P., & den Boer, J. (2014). EuroPruning – a new direction for energy production from biomass. *Agricultural Engineering*, *18*(3), 29–39. https://doi.org/10.14654/ir.2014.151.054

Dyjakon, Arkadiusz, & García-Galindo, D. (2019). Implementing agricultural pruning to energy in Europe: Technical, economic and implementation potentials. *Energies*. https://doi.org/10.3390/en12081513

EU 2015/1513. (2015). ILUC Directive. *Official Journal of The European Union*, 20–30. https://doi.org/http://eur-lex.europa.eu/pri/en/oj/dat/2003/l_285/l_28520031101en00330037.pdf

European Parliament. (2014). *Report on a 2030 framework for climate and energy policies (20132135(INI))*. http://www.europarl.europa.eu/sides/getDoc.do?pubRef=-//EP//NONSGML+REPORT+A7-2014-0047+0+DOC+PDF+V0//EN

García-Galindo, D., López, E., Gómez, M., Sebastián, F., Gebresenbet, G., Jirjis, R., Kern, J., Germer, S., Pari, L., Suardi, A., Dyjakon, A., DenBoer, J., Bukowski, P., Hunkin, S., Bundgaard-Jørgensen, U., Sagarna, J., Lapeña, A., Frackowiak, P., Adamczyk, F., … Poutrin, C. (2016). Europruning project: Summary of final results. *European Biomass Conference and Exhibition Proceedings*, *2016*(24thEUBCE).

Gebresenbet, G., Bosona, T., Olsson, S. O., & Garcia, D. (2018). Smart system for the optimization of logistics performance of the pruning biomass value chain. *Applied Sciences (Switzerland)*, *8*(7), 1–17. https://doi.org/10.3390/app8071162

Kinne, B. S. (2003). *Sustainable Energy Solutions in Agriculture* (G. Bundschuh, J.; Chen (ed.)). CRC Press: Rome, Italy, 2018.

Liu, J., R. Grisso, and J. C. (2013). Harvest Systems and Analysis for Herbaceous Biomass. In M. D. M. Rijeka (Ed.), *Intech: Vol. i*. https://doi.org/http://dx.doi.org/10.5772/57353

Mann, M. E., Cohen, R. D. H., Kernan, J. A., Nicholson, H. H., Christensen, D. A., & Smart, M. E. (1988). The feeding value of ammoniated flax straw, wheat straw and wheat chaff for beef cattle. *Animal Feed Science and Technology*. https://doi.org/10.1016/0377-8401(88)90019-3

McCartney, D. H., Block, H. C., Dubeski, P. L., & Ohama, A. J. (2006). Review: The composition and availability of straw and chaff from small grain cereals for beef cattle in western Canada. *Canadian Journal of Animal Science*, *86*(4), 443–455. https://doi.org/10.4141/A05-092

Monti, A., Di Virgilio, N., & Venturi, G. (2008). Mineral composition and ash content of six major energy crops. *Biomass and Bioenergy*. https://doi.org/10.1016/j.biombioe.2007.09.012

Motola, V., Colonna, N., Alfano, V., Gaeta, M., Sasso, S., De Luca, V., De Angelis, C., Soda, A., & Braccio, G. (2009). Censimento potenziale energetico biomasse, metodo indagine, atlante Biomasse su WEB-GIS. *Ricerca Sistema Elettrico, RSE/2009/1*, 141.

Picchi, G., Lombardini, C., Pari, L., & Spinelli, R. (2018). Physical and chemical characteristics of renewable fuel obtained from pruning residues. *Journal of Cleaner Production*, *171*, 457–463. https://doi.org/10.1016/j.jclepro.2017.10.025

Picchi G., S. R. (2012). Sradicatore Gottardo all'opera per fare biomassa da espianti. *LÍnformatore Agrario*.

Scarlat, N., Dallemand, J. F., Monforti-Ferrario, F., & Nita, V. (2015). The role of biomass and bioenergy in a future bioeconomy: Policies and facts. *Environmental Development*, *15*, 3–34. https://doi.org/10.1016/j.envdev.2015.03.006

Shirtliffe, S. J., & Entz, M. H. (2005). Chaff collection reduces seed dispersal of wild oat (Avena fatua) by a combine harvester. *Weed Science*, *53*(4), 465–470. https://doi.org/10.1614/WS-03-109R2

Spinelli, R., Nati, C., Pari, L., Mescalchin, E., & Magagnotti, N. (2012). Production and quality of biomass fuels from mechanized collection and processing of vineyard pruning residues. *Applied Energy*. https://doi.org/10.1016/j.apenergy.2011.07.049

Stelte, W., Sanadi, A. R., Shang, L., Holm, J. K., Ahrenfeldt, J., & Henriksen, U. B. (2012). Recent developments in biomass pelletization - a review. *BioResources*, *7*(3), 4451–4490.

Vis, M. W., & van den Berg, D. (2010). Harmonization of Biomass Resource Assessments. In *Biomass Energy Europe*. https://doi.org/10.13140/2.1.4643.8084

Walsh, M., Newman, P., & Powles, S. (2013). Targeting Weed Seeds In-Crop: A New Weed Control Paradigm for Global Agriculture. *Weed Technology*. https://doi.org/10.1614/wt-d-12-00181.1

Weiß, B. D., & Glasner, C. (2018). Evaluation of the process steps of pretreatment, pellet production and combustion for an energetic utilization of wheat chaff. *Frontiers in Environmental Science*. https://doi.org/10.3389/fenvs.2018.00036

Zhang, H., Lopez, P. C., Holland, C., Lunde, A., Ambye-Jensen, M., Felby, C., & Thomsen, S. T. (2018). The multi-feedstock biorefinery – Assessing the compatibility of alternative feedstocks in a 2G wheat straw biorefinery process. *GCB Bioenergy*, *10*(12), 946–959. https://doi.org/10.1111/gcbb.12557

6. Abstracts delle pubblicazioni realizzate durante il dottorato

Nella presente sezione sono riportati gli abstracts di otto lavori scientifici, di cui il dottorando è coautore, realizzati durante lo svolgimento del dottorato, pubblicati o in corso di pubblicazione (principalmente su riviste internazionali ISI). Gli articoli completi sono riportati in appendice.

6.1 Pruning Biomass Potential in Italy Related to Crop Characteristics, Agricultural Practices and Agro-Climatic Conditions

Pari L., Alfano V., Garcia-Galindo D., Suardi A., Santangelo E. (2018). Pruning Biomass Potential in Italy Related to Crop Characteristics, Agricultural Practices and Agro-Climatic Conditions. Energies. 2018; 11(6):1365.

Abstract: This work, developed under the EuroPruning Project, aims to look at relations between pruning biomass production and several factors related both to crop species and management. The aim is to find out mathematical relations that allow improvement of the biomass potential assessment. This is generally calculated using biomass production ratios. These ratios are variable due to the influence of several aspects. On the one hand there are crop characteristics—such as species, cultivar, and age—and on the other, crop management, which is often associated to local habits and conditions such as the training system, planting pattern, density, pruning methods, irrigation and climate. This work has been produced by gathering data from literature reviews and surveying. The subset of Italian records in the EuroPruning database consists of 70 records. Each record contains the biomass production ratio and eight agronomic variables. Additionally, a set of six climatic and agro-climatic groups of variables (in total 28 variables) have been added to each record. Moderate to good correlations have been found, especially with few climatic factors. As a result, two regression models are proposed for the evaluation of the vineyard and olive tree pruning biomass ratios for Italy and applied to assess pruning biomass potential.

Keywords: pruning availability; biomass potential assessment; correlation analysis; regression model; bioenergy

6.2 Current and innovative technologies for pruning harvesting: A review

Pari L., Suardi A., Santangelo E., García-Galindo D., Scarfone A., Alfano V. (2017). Current and innovative technologies for pruning harvesting: A review. Biomass and Bioenergy 107, pp. 398-410

Abstract: Pruning residues can provide a significant amount of biomass despite being rarely used as a renewable source to replace fossil fuels. Exploiting such residues entails creating a sustainable and cost-effective supply chain in which the harvesting and initial processing of the residues play a crucial role. The study is a detailed and accurate survey of the harvesting technologies available in Europe for harvest pruning. After defining the main harvest technologies and the distribution of manufacturers in Europe, the survey details the main groups of implements: shredders, chippers and balers. For each group, the most important configurations are discussed, together with the main characteristics of the machine. Some of the main innovations are detailed (modular machines, non-stop balers, densification of the biomass) which can improve the quality of the product and the economic sustainability of the chain.

Keywords: Harvest pruning, Shredder, Baler, Chipper, Agricultural residues, Mechanization

6.3 Pelleting Vineyard Pruning at Low Cost with a Mobile Technology

Toscano G., Alfano V., Scarfone A., Pari L. (2018). Pelleting Vineyard Pruning at Low Cost with a Mobile Technology. Energies. 2018; 11(9):2477.

Abstract: The goal of this work was to test a patented pruning harvester and a mobile pelleting system specifically designed for the vineyard agripellet chain. Biomass was characterized before and after storage and after the pelleting stage. The performance, the fuel consumption, and the work quality of the harvester were assessed together with the productivity and the power consumption of the mobile pelleting system. Production costs of pellet were estimated for the whole logistic chain, considering two scenarios: Storage and pelleting directly at the farm site or at a dedicated location at variable distance from the fields. For comparison, the direct production of chips without pelleting was considered. Results indicate that harvester performance was quite good and comparable with commercial solutions; the chips produced exhibited excellent storage performance, allowing direct pelleting without forced drying; the pellet quality was good comparable with that produced from forestry biomass. From an economic point of view, in-field pelleting was the most cost-effective solution, with a good margin of profit up to 57 t^{-1}; on the other hand, when transport to an intermediate storage centre is necessary, profit margin reduces gradually and fades off at an average 50 km distance from the fields.

Keywords: agripellet; biomass; bioenergy; mobile pelleting plant; logistic chain; pruning harvester

6.4 Testing open-air storage of stumps to provide clean biomass for energy production

Pari L., Scarfone A., Alfano V., Bergonzoli S., Gallucci F., Santangelo E. (2017). Testing open-air storage of stumps to provide clean biomass for energy production. Energies 10(11),1725

Abstract: When orchards reach the end of the productive cycle, the stumps removal becomes a mandatory operation to allow new soil preparation and to establish new cultivations. The exploitation of the removed stump biomass seems a valuable option, especially in the growing energy market of the biofuels; however, the scarce quality of the material obtained after the extraction compromises its marketability, making this product a costly waste to be disposed. In this regard, the identification of affordable strategies for the extraction and the cleaning of the material will be crucial in order to provide to plantation owners the chance to sell the biomass and offset the extraction costs. Mechanical extraction and cleaning technologies have been already tested on forest stumps, but these systems work on the singular piece and would be inefficient in the conditions of an intensive orchard, where stumps are small and numerous. The objective of this study was to test the possibility to exploit a natural stumps cleaning system through open-air storage. The tested stumps were obtained from two different vineyards, extracted with an innovative stump puller specifically designed for continuous stump removal in intensively-planted orchards. The effects of weathering were evaluated to determine the fuel quality immediately after the extraction and after a storage period of six months with respect to moisture content, ash content, and heating value. Results indicated interesting storage performance, showing also different dynamics depending on the stumps utilized.

Keywords: stumps; bioenergy; storage; fuel quality; orchards

6.5 Best available technologies to harvest cereal chaff

L. Pari, V. Alfano, A. Scarfone, S. Bergonzoli, A. Suardi, S. Lazar (2018). Best available technologies to harvest cereal chaff. Oral presentation. European Biomass Conference and Exhibition Proceedings 2018(26thEUBCE), pp. 77-8226

Abstract: This work has been developed under the AGROinLOG Project, "Demonstration of innovative integrated biomass logistics centres for the Agro-industry sector in Europe". An Integrated Biomass Logistics Center (IBLC), is based on the introduction of new production chains into existing agro-industries by using new biomass feedstock. The AGROinLOG Project dedicates great attention to investigate the potential of cereal chaff as a valuable resource. Made up of glumes, seed husk and rachis, it is valuable for animal feed or litter, or as feedstock for energy purposes. During cereal threshing, it is commonly left on the ground together with other thinner part of the cereal stems, whole or cracked kernels and weed seeds. Due to its value, many machineries builders has recently developed several systems for its recovery. The study represents a detailed and accurate survey of the harvesting technologies available at present in the market.

Keywords: threshing residues, combine harvester, straw baling, weed seeds, energy purposes, animal feeding.

6.6 Equipping a combine harvester with turbine technology increases the recovery of residual biomass from cereal crops via the collection of chaff

Suardi A., Stefanoni W., Alfano V., Bergonzoli, S., Pari, L. (2020). A harvester combine equipped with a turbine system to increase the total residual biomass from cereal crops by collecting the chaff. Energies 2020, 13, 1572.

Abstract: In cereal crops, chaff is a valuable lignocellulosic by-product that accounts for more than 50 Mt y^{-1} in Europe and is suitable for bioenergy purposes. Chaff is usually not collected due to the lack of combine harvesters that have the capability to handle it properly. The present two years experimental study investigated the hypothesis that the overall biomass collected in wheat crop can be increased by equipping the combine harvester with an aftermarket device. Chaff, discharged from the combine harvester-cleaning system, is collected by the turbine that delivers it either on the swath or on a lateral trailer towed by a tractor. The performance of all machines involved in the harvesting (combine harvester, tractor, baler, and trailer) were assessed. The chaff was collected in bales with the straw (A mode) and separately on a trailer (C mode). Comparisons with non-collected treatment (B mode) were performed in order to estimate the total chaff collected and the biomass losses. The results showed that 1.79 t FM ha^{-1} per year of chaff could be collected when baled with the straw, whereas 1.27 t FM ha^{-1} were collected separately on a trailer. Both field and material capacity were not negatively affected by the chaff collection. Therefore, our study confirmed the hypothesis that turbine technology is a valid solution for increasing the total residual biomass collected in cereal cropping for energy purposes.

Keywords: wheat; straw; weed seed; biocommodity; threshing; bioenergy

6.7 Maize cob harvesting: first assessment of an innovative system

L. Pari, S. Bergonzoli, A. Suardi, V. Alfano, A. Scarfone, S. Lazar (2018). Maize cob harvesting: first assessment of an innovative system. Poster presentation, European Biomass Conference and Exhibition Proceedings 2018(26thEUBCE), pp. 323-325

Abstract: The maize cob is still an untapped biomass, being rarely used and normally left on the soil. Maize cobs are considered to have a very limited nutritional value for the soil or as animal food. Therefore, collecting all of it for energy or bio-based materials production will not have negative impact on the soil neither will affect food security. The different tests were performed during maize grain harvesting in September 2017 using a commercial combine harvester machine equipped with the Harcob system. It was possible to harvest 2 t ha^{-1} of cob, with a material capacity of 4.1 t h^{-1}. The cob losses were lower than 20%, highlighting the right functioning of the system. Moreover, the unloading operation is performed by an innovative auger system that ensures no blocking problems and requires around 3 minutes, allowing the discharging of maize cob grain at the same time.

Keywords: agricultural residues, harvesting, maize

6.8 Economic distance to gather agricultural residues from the field to the integrated biomass logistic centre: A Spanish case-study

Suardi, A., Bergonzoli, S., Alfano, V., Scarfone, A., Pari, L. (2019). Economic distance to gather agricultural residues from the field to the integrated biomass logistic centre: A Spanish case-study. Energies 12(16),3086

Abstract: A big amount of agricultural residues are generated from crop production and partially remain in the field after harvest. Removing the excess of residues after crop harvesting can increase farmer income, providing feedstock that could be used for industrial and energy purposes. The costs for collection and transport of straw and stalks are site- and region-specific and depend on the availability of agricultural residue and on how much of the residue is removed from any specific field or location. If the biomass is baled then it is required to upload the bales on a trailer, transport and unload all the baled biomass to the storage center. On the other hand, if a self-loading wagon is used the loose biomass collected, it must be unloaded every time the wagon is completely full. The distance and the harvesting system used influence the costs and should be analytically studied to avoid turning a possible profit into a disadvantageous business. The research represents a real case study to evaluate, which is the maximum distance to the biomass logistic center from which it is more economically convenient to gather the wheat and corn residues in bales instead of using a self-loading wagon. The results show a lower harvesting unitary cost for the self-loading forage wagon respect to the baling system. Although the study showed delivery distances over 11.4 km for wheat straw and 16.0 km for maize stalks, the use of the self-loading forage wagon is no longer convenient, and baling is the preferred harvesting system.

Keywords: agricultural residue; maize stalk; cereal straw; harvesting; baler; self-loading wagon; cost analysis; transport cost

7. Conclusioni

Le attività di ricerca realizzate nel corso del dottorato hanno messo in luce la validità, sia dal punto di vista tecnico che economico, delle soluzioni meccaniche analizzate, destinate al recupero e alla gestione di alcuni residui agricoli caratterizzati da enormi potenzialità in termini di disponibilità e caratteristiche, ma finora scarsamente o, per nulla, utilizzati.

È stato dimostrato come queste potenzialità possono essere sfruttate in modo sostenibile e redditizio, attraverso l'organizzazione di un'efficiente filiera di approvvigionamento e, come la meccanizzazione abbia un ruolo chiave nel contenere i costi della raccolta e della logistica. Queste infatti costituiscono le fasi più onerose della filiera di approvvigionamento di biomasse residuali del settore agricolo, caratterizzate da bassa densità volumica e, spesso, anche dalla dispersione sul territorio.

Nel caso delle potature, la scelta della tecnologia di raccolta deve essere valutata in funzione dell'estensione e delle caratteristiche del bacino di approvvigionamento e delle fasi successive di trasporto, stoccaggio, movimentazione ed eventuale pretrattamento. Meritevole di segnalazione è l'organizzazione logistica adottata dall'impianto Fiusis di Calimera (LE), analizzato come caso studio e modello di riferimento nell'ambito del progetto AGROinLOG. L'impianto da 1MWe è alimentato esclusivamente da potature di olivo, ritirate a titolo gratuito dalle aziende limitrofe con due cantieri di raccolta alternativi, a seconda della dimensione aziendale: trincia-caricatrice per aziende con meno di 400 piante o cippatrice fissa di tipo forestale per aziende più estese. In entrambi i casi il prodotto cippato viene stoccato presso le stesse aziende e prelevato durante l'anno in funzione delle necessità dell'impianto.

Nelle condizioni più tipiche delle aziende agricole italiane, caratterizzate da frammentazione e dispersione sul territorio, una soluzione molto interessante si è dimostrata essere il cantiere mobile per la pellettizzazione delle potature di vite. A seconda della dimensione del bacino di approvvigionamento, il principale vantaggio del sistema mobile consiste nella riduzione dei costi di trasporto della biomassa. Quando la pellettizzazione avviene direttamente in campo, i costi di produzione dell'agripellet sono redditizi con un alto margine economico rispetto al prezzo di mercato del pellet. Il margine di profitto diminuisce gradualmente quando il cippato deve essere trasportato all'esterno dell'azienda e quando la distanza di trasporto aumenta. Dal punto di vista qualitativo, inoltre, l'agripellet ha mostrato parametri di buona qualità, paragonabili a quelli del pellet ottenuto dalla silvicoltura a turno breve, ad eccezione del contenuto di ceneri e rame.

Un'altra risorsa analizzata, che si è dimostrata particolarmente interessante, per quantità e qualità, è la biomassa di espianto a fine ciclo di vita che si rende disponibile per il rinnovo dei frutteti. Nello specifico, le prove realizzate nell'estrazione e successivo stoccaggio delle radici di un vigneto, hanno mostrato ottime prestazioni dell'innovativo sradicatore utilizzato e interessanti indicazioni dalla fase di stoccaggio. La macchina ha mostrato una produzione oraria media di circa 9 t h^{-1} e 7,5 t ha^{-1}, con una percentuale di terreno adeso alle radici molto limitata. Considerando gli attuali costi del cippato ad uso energetico, la vendita di tale prodotto potrebbe generare un reddito da un'operazione onerosa e comunque inevitabile, ed evitare i costi di smaltimento normalmente sostenuti dall'azienda. La possibilità di stoccare le radici in cumuli all'aperto senza perdite sostanziali di sostanza secca, ma migliorandone addirittura la qualità per effetto della rimozione della terra grazie al dilavamento associato all'azione di gelo e disgelo, rende auspicabile la nascita di filiere industriali.

Relativamente agli scarti di trebbiatura, le soluzioni meccaniche analizzate si sono dimostrate particolarmente efficienti. Per quanto riguarda i tutoli del mais, il corretto funzionamento del sistema Harcob, unica esperienza conosciuta in Europa, ha mostrato la concreta possibilità di valorizzare una risorsa importante che attualmente viene lasciata in campo, senza influire sui tempi di raccolta della granella di mais. Sono stati raccolti in media 2 t ha^{-1} di tutoli, con una produttività oraria di 4,1 t h^{-1}. I tutoli costituiscono un ottimo substrato per alimentare in co-digestione un impianto di biogas. Possono in alternativa essere essiccati per la produzione di mangimi o lettiera animale.

Per quanto riguarda la raccolta della pula dei cereali sono state censite soluzioni commerciali ed altre allo stadio prototipale con diverse finalità. Le tecnologie utilizzate in Australia hanno come obiettivo principale la rimozione dei semi delle infestanti. Le tecnologie francesi, invece, sono finalizzate al recupero della pula per una destinazione energetica o per la produzione di foraggio o utilizzo come lettiera. L'esperienza realizzata in Francia con una tecnologia a turbina, ha evidenziato l'efficacia del sistema pur nella sua semplicità e versatilità.

Il sistema, testato in due anni consecutivi, non ha influenzato negativamente i tempi di raccolta della mietitrebbia e ha consentito in media il recupero di 1,79 t ha^{-1} di pula insieme alla paglia (pari ad un incremento da 30% al 50% della biomassa imballata) e di 1,27 t ha^{-1} di pula separatamente su rimorchio.

L'ultima attività, non per importanza, riportata nella tesi riguarda la logistica, attraverso il confronto tecnico economico di due cantieri alternativi per la raccolta e trasporto di paglia e stocchi. La metodologia implementata per individuare la distanza di convenienza economica rispetto al centro di stoccaggio nella scelta tra i due cantieri, anche se testata per due casi specifici in Spagna, può essere un valido supporto per orientare le scelte nella gestione logistica di altre tipologie di biomassa ed in altri contesti.

In conclusione si può affermare che esistono biomasse residuali del settore agricolo con enormi potenzialità sia per la bioenergia che per i molteplici nuovi utilizzi delle nascenti industrie biobased, ma ancora poco sfruttate per ostacoli legati principalmente alla convenienza economica della raccolta e trasporto. Con il presente lavoro è stato dimostrato, almeno per le risorse selezionate, che esistono soluzioni meccaniche in grado di superare tali ostacoli, contribuendo alla sostenibilità tecnica ed economica di operazioni fondamentali per il nascere di filiere industriali per la valorizzazione di residui in preziose risorse.

8. Appendice - Pubblicazioni realizzate durante il dottorato

Article

Pruning Biomass Potential in Italy Related to Crop Characteristics, Agricultural Practices and Agro-Climatic Conditions

Luigi Pari [1], Vincenzo Alfano [1,*], Daniel Garcia-Galindo [2], Alessandro Suardi [1] and Enrico Santangelo [1]

[1] Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria (CREA), Centro di ricerca Ingegneria e Trasformazioni agroalimentari, Monterotondo, 00016 Rome, Italy; luigi.pari@crea.gov.it (L.P.); alessandro.suardi@crea.gov.it (A.S.); enrico.santangelo@crea.gov.it (E.S.)

[2] Research Centre for Energy Resources and Consumption (CIRCE), 50018 Zaragoza, Spain; daniel.garcia@fcirce.es

* Correspondence: vincenzo.alfano@crea.gov.it; Tel.: +39-069-067-5315

Received: 28 March 2018; Accepted: 23 May 2018; Published: 28 May 2018

Abstract: This work, developed under the EuroPruning Project, aims to look at relations between pruning biomass production and several factors related both to crop species and management. The aim is to find out mathematical relations that allow improvement of the biomass potential assessment. This is generally calculated using biomass production ratios. These ratios are variable due to the influence of several aspects. On the one hand there are crop characteristics—such as species, cultivar, and age—and on the other, crop management, which is often associated to local habits and conditions such as the training system, planting pattern, density, pruning methods, irrigation and climate. This work has been produced by gathering data from literature reviews and surveying. The subset of Italian records in the EuroPruning database consists of 70 records. Each record contains the biomass production ratio and eight agronomic variables. Additionally, a set of six climatic and agro-climatic groups of variables (in total 28 variables) have been added to each record. Moderate to good correlations have been found, especially with few climatic factors. As a result, two regression models are proposed for the evaluation of the vineyard and olive tree pruning biomass ratios for Italy, and applied to assess pruning biomass potential.

Keywords: pruning availability; biomass potential assessment; correlation analysis; regression model; bioenergy

1. Introduction

Bioenergy has a primary role in achieving the target set in the national Renewable Action Plans (nREAP), accounting for almost 54.5% of these [1]. The development of the bio-based economy has resulted in an increased demand for biomass, also for non-energy purposes, so that there is a competition between the alternative uses [2]. The bioeconomy fosters the hierarchical utilization of biomass, based on the "cascade principle" [3]. Namely, biomass should be used according to its pyramid value (pharmaceutical and fine chemicals, food and feed, chemicals and materials, transportation fuels, power and heat). As a last resort, at the bottom of the cascade, the low-value bulk biomass should be used for biofuels and the production of electricity and heat [4]. In this framework the evaluation of biomass availability is crucial for accurate planning for a sustainable supply of a renewable, but not inexhaustible source [5].

The recent guidelines of the European energy strategy, transposed in the national legislation, address more and more the development of bioenergy for the predominant use of residual biomass, by-products and wastes from the agro-forest and agro-industry sectors, restricting the use of biomass specifically produced (energy crops) in compliance with strict sustainability criteria [6]. The exploitation of agricultural residues for energy production fits fully the new vision, avoiding competition for farmland utilization.

Among agricultural residues, prunings are an important energy resource, both in quality and quantity [7]. According to recent estimates, in Europe more than 13 million tons (over dry basis) of pruning biomass is available from the main orchards each year [8], in Italy around 6 million tons are produced yearly (including uprooted biomass) [9]. However, this resource is still minimally exploited due to the absence of an organized chain and, above all, a clear knowledge of its availability over time and space.

In the last years several studies have assessed the biomass potential in Europe and in Italy from agricultural residues, including prunings. Their results are often discordant or not directly comparable due to the different purposes (research oriented, decision making support), scale (national, regional, local level) and methodologies applied.

As explained by the referential EU projects BEE (BEE—Biomass Energy Europe) and CEUBIOM (CEUBIOM—Classification of European Biomass Potential for Bioenergy Using Terrestrial and Earth Observations), whose aim was to harmonize and improve the consistency, accuracy and reliability of biomass assessments, current methods use a wide range of approaches (theoretical, technical, economical and sustainable potential), methodologies (statistical or GIS based), assumptions and datasets that leads to different estimates of biomass potentials [10].

The use of ratios in biomass production is quite extended, usually expressed in terms of production per hectare (t ha^{-1}) or per unit of product (kg of pruning per kg of fruit). The former is usually referred to as the residue to surface ratio (RSR), and the latter as the residue to product ratio (RPR). However, such indices represent an average of the conditions, and are extremely variable, as explained by García-Galindo et al. in 2007 and 2016 [8,11], which was empirically recorded in several places or obtained from the literature; their application gives a rough estimate and is not accurate of the real potential when aiming to better know the local potentials in a downscaling approach.

The amount of prunings depends, in fact, on several factors that are on one hand directly correlated to crop characteristics, such as species, cultivar, rootstock and age, and, and on the other to agronomic practices, often associated to local habits and conditions (training system, planting pattern, density, pruning methods, irrigation regime, type of soil and climate). For instance, the layout for grapevines can be extremely variable: the plants per ha may vary from 1000 in arid zones to 4000 in fertile soils, to 6000 in intensive rich soils [12]. The density of olive orchards in the Mediterranean area varied from 70 to 150 trees ha^{-1} in traditional plantations to higher densities (200–450 trees ha^{-1}) and higher yields, and finally, a new type of olive orchard (super-high-density hedgerow) with densities ranging between 1500 and 2500 trees ha^{-1} [13,14].

The choice of rootstock is one of the main factors directly driving the growth and the vigor of fruit trees [15–17]. The scion–rootstock couple determines the root-to-shoot signaling, resulting in different lengths of the shoot, degree of branching, and crown volume [17,18]. In apples, the Malling rootstocks (M and MM series) were of pivotal importance in producing a range of tree sizes [15,18]. The adoption of intensive systems in olives relies on the availability of low-vigor rootstock with high rooting ability and the ability to control scion vigor [19–21]. However, the target of rootstock selection has been not limited to the size of the canopy, but is involved in other issues such as disease/pest resistance and abiotic tolerance [16,22]. Grapevines are one of the most glaring examples of the successful use of *Phylloxera*-resistant rootstocks to grow susceptible varieties in presence of the destructive aphid [16,23]. However, recent works have emphasized in grapevines the role of rootstock in determining the response of the scion to drought [24,25], and different abiotic stressors [22].

The EuroPruning Project was assigned a specific task, decided at the first stage to explore possible correlations with pruning material. The aim is to obtain regression models for different crop species or guides for zoning Europe into areas where different biomass production ratios can be applied when preparing Pan-European biomass inventories of pruning potentials [26].

Previous works on biomass accumulation and pruning production, based on systematic sampling campaigns, have identified significant correlations with many aspects mentioned above. Velazquez-Martí and co-workers [27–29] verified in different parcels along the east coast of Spain statistical significances for vineyards, olive trees and almonds, identifying regression models that correlated the amount of pruning, per plant or per hectare, with the irrigation regime, age, plant height, diameter of the crown, diameter of the stem, growing space per tree, fruit production, etc.

The scope of the work done under the EuroPruning Project is at a much higher hierarchical level with a top-down approach by using biomass production ratios observed by third parties in several countries of Europe, aiming at obtaining relevant correlations and confidence regression models. In particular, the present work analyses the subset of data obtained for the Italian territory. The approach is similar to some other studies that tried regression models for herbaceous crops, such as the ones performed by Scarlat et al. in 2010 and 2011 [30,31], which carried out correlations and regression analysis to determine the total straw from cereal and sunflowers accordingly to the yield of the main product (grain and seeds, respectively), based on literature publications of third authors.

Crop yield depends upon specific local agro-ecological conditions (climate, precipitation pattern, soil properties, etc.), plant varieties, farming techniques, and more [32]. Its correlation with residual biomass allows in a way to account for reality, but not enough for a downscaling analysis, being only one of several crops and site specific aspects that can influence the pruning production.

In Italy, the methodology developed in 1994 by AIGR (today known as the AIIA—Italian Agricultural Engineering Association) and ENEA (the Italian National Agency for New Technologies, Energy and Sustainable Economic Development) is widely utilized to assess agricultural residues, both at NUTS-2 (Nomenclature of territorial units for statistics) [9,33] and NUTS-3 level [34,35]. It is based on crop-specific residue to product ratio. Although RPR is a better approach than RSR in regard to lower variability [11], depending on the scale of the study the utilization of the same mean value per species can gives an unreliable estimation, particularly in a country such as Italy with extremely variable conditions from north to south.

The present study has the ambitious purpose to improve the estimations through the use of site specific RSR values. Namely, two regression models, respectively for vineyards and olive trees, have been built, allowing the calculation of a specific residue to surface ratio for each Italian province.

2. Materials and Methods

2.1. Database Implementation

A database was created through a survey work and a literature review. The goal was to identify factors related to crop species and management that can influence pruning biomass production.

For that purpose, main factors were placed into a form for the surveying work and into a table for registering the data existing in literature.

2.1.1. Survey

Farmers cultivating orchards, vineyards and olive groves, specialists, and agricultural cooperative technicians were contacted by phone or direct interview. They were asked, for their specific crop, to describe as much as possible a homogeneous reality representative of a specific reference zone, highlighting the differences both in terms of productivity and crop management.

The main information requested was: species and variety cultivated; planting layout; training system; plantation and renovation age; presence and type of irrigation; period, frequency, degree and type of pruning (manual, mechanical); yield and moisture of pruning (measured or estimated); management of pruning (burning in the field, shredding and burying, household firewood, etc.).

A parameter of intensification was created, as described by [8]; its values are 0, 1 or 2, assigned according to two characteristics of the fields: irrigation regime and training system. Value 0 is given to traditional training systems (vase, standard) under rainfed conditions. Value 1 is given to traditional training systems, but under irrigated regimes. Value 2 is assigned when training systems are intensive (cordon, espalier, fan, palmette) and irrigated.

2.1.2. Literature Review

Several scientific articles and technical reports were selected among Italian works where pruning production was measured directly on the field, even though it was not always their main purpose. The information gathered were: species, variety, residue to surface ratio (min, average, max), method of measuring and assessment (per row, per parcel, etc.), year of measurement, moisture content, system and frequency of pruning, harvesting efficiency (if mechanical), training system, age of the plantation, density, irrigation, productivity, nearest city, and geographic coordinates.

The information was listed in an excel worksheet. The lacking data were completed via direct contact with the authors of each work.

2.1.3. Addition of Further Variables

In order to extend the analysis to environmental conditions, potentially related to RSR, a set of climatic, agro-climatic and agro-ecological parameters were added to each database record.

These parameters were extracted from open data sources in form of continuous raster datasets. Discrete values have been taken in correspondence of each point recorded in the database, using an overlay GIS map with their locations.

Main parameters have been obtained from the Global Agro-Ecological Zones (GAEZ is a methodology developed over the last 30 years by the Food and the Agriculture Organization of the United Nations (FAO) and the International Institute for Applied System Analysis (IISA), aimed at assessing agricultural resources suitability and crop potentials.) (GAEZ) portal (such as length of growing period, net primary productivity, etc.) [36]. Some datasets have also been obtained from the Consortium for Spatial Information (The Consortium for Spatial Information (CSI) is a spatial science community that supports the Global Agricultural Research Partnership (CGIAR) with spatial analysis, GIS, and remote sensing.) (CGIAR-CSI) portal (such as the global aridity index, global potential evapotranspiration and Ecocrop suitability index) [37].

Climate classifications were also extracted from the world map of the Köppen-Geiger climate classification [38], and the European biogeographical regions of the EEA (European Environmental Agency).

2.2. Correlation Analysis and Implementation of Regression Models

A correlation analysis among RSR, as a dependent variable, and the remaining parameters aiming to be explanatory variables, has been performed. IBM SPSS Statistics for Windows (19.0, IBM Corp., Armonk, NY, USA) was used for the analysis. A non-parametric analysis was selected and the Spearman correlation coefficient (*$*) was chosen to measure the strength of this relation. A matrix of correlation was built in order to study:

1. The strength of the relation or the value of the coefficient *$*, according to the following ranking: weak 0.1 < *$* < 0.3; moderate 0.3 < *$* < 0.6; strong 0.6 < *$* < 0.9.
2. The reliability of the relation or the *p*-value: only significant correlations with a confidence level of 0.05 were accepted.
3. Possible multicollinearities or relations between independent variables themselves, which could make a future regression analysis incorrect.

After correlation analysis, a regression study was performed with the variables showing a better relation with the pruning ratio. The aim was to reach a mathematical equation that could predict the amount of pruning under certain conditions.

2.3. Ramp Function and Geographical Implementation

Ramp functions have been created in order to avoid extrapolation and projections out of the values predicted by the sample (Figure 1). The hypothesis is that, given a linear relation, the value of the dependent variable out of a sample size remains constant. Horizontal (constant) function for the X values lower than the lower threshold, and higher than the upper threshold, has been built.

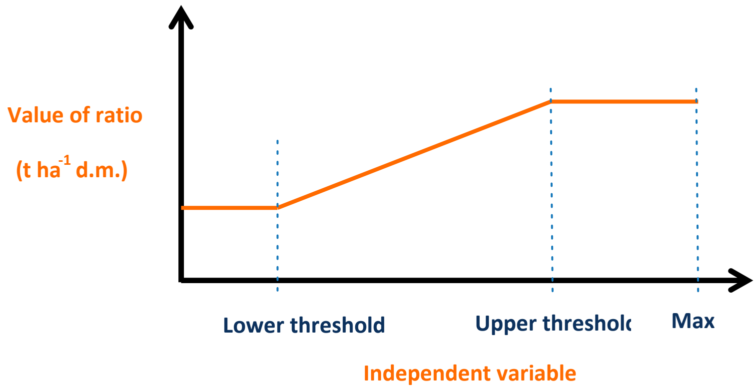


Figure 1. Ramp function utilized to avoid extrapolation out of the values predicted by the sample.

QGIS (Version 2.14 "ESSEN") has been utilized to apply ramp functions in order to convert the agro-climatic coverages into a continuous pruning ratio dataset by NUTS-3 in Italy.

3. Results and Discussion

3.1. Direct Survey and Literature Analysis

A total of 14 surveys were filled by farmers (10) and by experts (4). The survey included: olive groves (3), vineyards (3), hazelnuts plantations (1), peach (2), citrus (2), plum (1), and apple orchards (1).

The overall analysis of the surveys pointed out a great variability among crops and within the same crop, for the amount of pruning due to differing crop management (training system and planting pattern) and climate conditions (from North to South) (Table 1). Regarding the destination of the prunings, in most cases they were shredded and left on the soil or piled and burnt in the field.
Occasionally they were used as local firewood.

Concerning the literature review, a total of 14 works, 13 scientific articles and 1 technical report not yet published, have been analyzed. The review showed that information gaps are quite usual. In most of cases, authors did not report sufficient data to carry out the statistical analysis. For instance, some authors did not publish site of collection, variety of crop, or crop layout. In those cases, the new information gathered through direct contact with authors have integrated the literature analysis in order to fill these gaps.

In seven articles the data referred to commercial harvesters (balers or chippers) tested in different orchards and places [39–45]; in one case it was used a prototype [46]. The amount of pruning was calculated taking into account the performance of the machines (harvesting efficiency) reported in the articles or by asking the authors. In the last six works, data was directly collected in the field on sampling plots [47–51].

The crops analyzed were: vineyards (7), olive trees (6), apple (3) and pear orchards (1). The data was collected in the North of Italy from five works, from seven documents in Central Italy and from three documents in the South.

The outcome suggests a great variability of the residue to surface ratio (RSR). Regarding the vineyard, it ranged from 0.11 t ha^{-1} [45] to 7.11 t ha^{-1} [49]. Olive tree values went from 0.6 t ha^{-1} [40] to 7 t ha^{-1} [47], whereas the apple ranged from 1 [51] to 9.8 t ha^{-1} [42].

Table 1. Main results of the survey analysis.

Species	Site	Training System	Planting Pattern	Irrigation System	Pruning Frequency	Pruning Period	RSR (t ha^{-1} y^{-1})
Olive tree	Caltanissetta (South)	Vase	12 × 12	No	Biannual	December–January	1.1–1.4
Olive tree	Sabina (Center)	Vase	6 × 6	No	Annual (60%)	February–March–April	2.1–2.8
Olive tree	Spoleto (Center)	Vase	6 × 7	No	Biannual	February–March–April	2.1–2.8
Vineyard	Biella (North)	Espalier	4 × 4	No	Annual	November–December–January–February	0.6–0.8
Vineyard	Castel Bolognese (North)	Pergoletta	6.6 × 1.3	No	Annual	December–January	1.5–2.8
Vineyard	Vittoria (South)	Tendone	2.5 × 2.5	Drip	Annual	November	4.8–6.4
Hazelnuts	Viterbo (Center)	Vase	5 × 6	No	Annual	October–November–December	1.27–3.03
Peach	Vercelli (North)	Vase	5 × 4	Surface	Annual	February–March–April	2.5
Peach	Ravenna (North)	Vasetto ritardato	5.5 × 3	Drip	Annual	February–March–July	0.5–0.6
Citrus	Sibari (South)	Globe	5 × 5	Drip	Annual	June–July	8
Citrus	Vittoria (South)	Globe	5 × 5	Drip	Annual	June	2
Plum	Ravenna (North)	Palmetta libera	4.3 × 2.5	Drip	Annual	March–April	0.7–0.8
Apple	Vercelli (North)	Solaxe	3.5 × 1.5	Surface	Annual	November–December–January–February–March	5–7

Moreover, the analysis shows a wide range of varieties, training systems and densities for each species. The studies account for more than 10 different varieties of vineyard. The training system is in most cases the "espalier", while the density ranges from 2600 to 6200 plants per hectare. Six different varieties of olive have been analyzed, in all cases with the traditional training system of the "vase", but with density ranging from 100 to 550 plants per hectare.

Seven different varieties of apple have been studied, in part cultivated with the traditional "espalier" system, and in other cases with intensive systems such as the "slender spindle", with density ranging from 700 to 3500 plants per hectare. Two varieties of pear tree have been analyzed, with the traditional espalier plantation and density ranging from about 1200 to 1400 plants per hectare.

3.2. Database Implementation

A database with 65 valid records was built, 8 obtained from work surveying and 57 from literature research (Table 2). Incomplete or unreliable records were discarded. Moreover, the crops with too few records to be used in any model (namely 2 records for stone fruit, 2 for citrus and 1 for hazelnuts), were excluded by further analysis. The records ready for statistical analysis refer to 23 geographic positions (Figure 2).

Figure 2. Locations of database records in Italy.

Table 2. Number of records and locations analyzed in the database. Residue to surface ratio, RSR (mean, minimum and maximum) for each crop.

Crop	Records	Locations	Mean RSR (t ha^{-1})	Minimum	Maximum
Vineyard	40	10	1.15 ± 0.51	0.11	2.57
Olive	12	10	1.90 ± 1.44	0.35	5.46
Pome fruit	13	3	1.88 ± 0.87	1.00	5.64
TOTAL	65	23	-	-	-

Each record includes the pruning yield and 8 agronomic variables obtained from survey and literature reviews, and 28 agro-climatic variables selected from open data sources as explained in Section 2.1.3 (Table 3). Uncertain variables like cultivar, though relevant in determining the pruning yield, were not included. The uncertainty was due to the goal of the reviewed articles, which focused on the harvesting mechanization rather than specific agronomic aspects.

The full set of records for each crop can be found in the Supplementary Material (Table S1).

Table 3. Variables implemented in the database.

Factor Type	Source	Variable Implemented	Type of Variable/Comments
Crop	Literature & Surveys	3 variables: Species (Nom), Crop group (Nom), Age (Cont)	Specific data of the crop
Crop management	Literature & Surveys	4 variables: Density (Cont), Training system (Nom), Irrigation (Dic), Intensification (Ord)	Agronomic
Climate	[36]	1 climate type: Thermal climate (Ord)	General variable (non-crop specific)
Agro-climatic indicators (ACI)	[36]	3 variables (all Cont): LGP (length growing period), NPP (net primary productivity) and reference Evapotranspiration (ETP)	General
Agro-climatic potentials (ACP)	[36]	3 variables (all Cont): ACP_ab (*), ACP_rel (*), ACP_OL	Two general variables and one agroclimatic may be specific for Olive production. These variables evaluate potentials of a crop given specific climatic conditions
Agro-ecological potentials (AEP)	[36]	10 variables (all Cont): AEP_ab (*), AEP_rel (*), AEP_OL, AEP_Sidx (*), AEP_Sidx_OL, AEP_AG (*), AEP_AG_rel (*), AEP_AG_OL, AEP_AG_Sidx (*), AEP_AG_Sidx_OL	6 variables correspond to a reference crop potential. 4 specific for olive. These variables evaluate potentials of a crop given specific climatic and soil conditions
Actual yields (YLDs)	[36]	5 variables (all Cont.): Ylds_ab (*), Ylds_rel (*), Ylds_OL_ab, Yld_gaps (*), Yld_gaps_OL	3 of the variables correspond to a reference crop. Yields refer to downscaled actual yield utilised to build the actual yields of a reference crop. Yield gaps (between agro-ecological and actual potentials)
Agro-climatic indicators (ACI)	[37]	2 variables (all Cont.): Global-Aridity index (AR_idx), Global Potential Evapotranspiration (PET_idx)	General
Agro-climatic potentials (ACP)	[52]	4 variables (all Cont.): mECO_Wclim, ECO_wclim_th, ECO_ccm, ECO_ccm_th	Ecocrop suitability index represent the suitability (0 to 100%) of a crop. Two climatic databases are utilised by Ecocrop, producing two different datasets. When the moisture regime is not evaluated, variable is only thermal (th)
Climate	[38]	1 variable: Köppen-Geiger climate classification (Ord)	General
Climate	[53]	European biogeographical regions (Ord)	General

Variable types: Nom: nominal; Dic: Dichotomous; Ord: ordinal; Cont: continuous. (*) Variables of agro-climatic potentials referred to a reference crop (required averaging of several crops). This reflects land production potentials.

3.3. Correlation and Regression Analysis

A correlation analysis has been produced only for vineyard, olive and pome fruit crops, since the data recorded for the other crops were not sufficient (see Table 2).

In general, according to the Spearman correlation, the level of association has shown only weak to moderate correlations between pruning potential (the dependent variable) and some proposed explanatory variables.

According to the limits of the Spearman's coefficient reported in Section 2.2, the correlations found for vineyards were weak to moderate, ranging from 0.355 to 0.481. Only the intensification factor corresponds to data obtained from the fields. The rest is related to agro-climatic variables.

Beyond the intensification, the analysis did not show any correlation in olives. No statistically significant correlation between variables has been found. However, some results are presented in Table 4, since their correlation coefficient was weak to moderate.

Table 4. Result of the correlation analysis between the pruning biomass production ratio (t d.m. ha^{-1}) and the field and climatic variables.

Crop	Sample Size	Parameter	ϱ Spearman	Confidence (*p*-Value) [1]
Vineyard	40	Intensification	0.357	*
		Koeppen climates	0.335	*
		PET	0.450	**
		ACP_ab	0.477	**
		Ecocrop (Wclim)	0.481	**
		Ecocrop (ccm)	0.431	**
Olive	12	Intensification	−0.418	**
		Koeppen climates	0.461	n.s.
		Ecocrop (Wclim)	0.367	n.s.
Pome Fruit	13	ACP_ab	0.428	n.s.
		Ecocrop (Wclim)	0.299	n.s.

[1] Were reported, * $p < 0.05$ and ** $p < 0.001$ probability levels. n.s. not significant.

In fact, in this study correlations were not expected to be strong or very strong, but the main aim was to find some degree of correlation, suggesting that the pruning production can be partially explained by one or several of the proposed explanatory variables. Moreover, the strength of the correlation coefficients depends on the scope of the analysis and type of field of science. In dendrometric studies, for example, a correlation factor $ > 0.9 could be expected. In social sciences however, correlations of $ > 0.5 can be considered already relevant [54].

In our case, acknowledging that intensification was affected by factors with a social profile, such as local preferred training system and management methods (irrigation regime, pruning methods and degree of cutting), the results are remarkable.

Intensification in olives shows a negative correlation, meaning that the more the plantation is intensified, the lower the biomass production. It's possible that olive varieties selected for intensified plantations in higher density have less vigor and dedication to wood production than traditional varieties.

Also in the case of pome fruit trees, no statistically significant correlation was present. Only two climatic variables showed some acceptable correlation with the biomass production ratio; the agro-climatic potential and the Ecocrop suitability index.

The values obtained for the Spearman correlation factors are weak to moderate, ranging 0.3 to 0.48. The corresponding R2 values range from 0.09 to 0.23. This means that regression analysis will probably lead to poorly fitted regression curves. In actuality, Spearman's rank correlation test is a nonparametric method which does not carry any assumptions about the distribution of the data. It is useful when data are not distributed according to a normal distribution and/or in the presence of very small samples (7 to 30 pairs of data). However, it is known that small samples can increase the imprecision of the estimate. This may increase the likelihood of obtaining false negatives, i.e., the absence of an effect that could really be present. In the case of olive and pome fruits the sample size could have generated such an effect.

The regression models were tested, and they were not reliable for the intensification factor. For the agro-climatic variables ACP_ab and Ecocrop_wclim the models demonstrated independence, linearity and heteroscedasticity. However, they failed to show a normal distribution of residues.

Since the field parameters vary from record to record, while the agro-climatic ones vary according to the resolution of the data sources (5 arc-minute grid-cell resolution, that is cells of about 50 km^2 size), the database has been restructured, in order to improve the correlation with the climatic factors.

The biomass production ratios of the records falling into the same grid-cell have been combined in a single record with an average value.

The size of the aggregated database is shown in Table 5. The sample size has been quite reduced in the case of vineyards, in which records are distributed in 10 different cells, and pome fruit, which were sited into only two grid-cells.

Table 5. Number of records analyzed for the full database and for the average cell aggregated database.

Crop	Full Database	Database Aggregated Values by GIS Cell
Vineyard	40	10
Olive	12	10
Pome fruit	13	2
TOTAL	65	22

As a result of the sample size, bivariate correlation analysis has been done only for vineyard and olive crops, to find relations between biomass yield and climatic variables. The results of the correlation are summarized in Table 6 for vineyards and olives. There is an observed improvement in the agro-climatic parameters provided by the ECO-CROP database, achieving a good correlation level for vineyards. In the case of olives, the improvement was only quite marginal, and the correlation analysis failed the confidence test.

Table 6. Results of the correlation analysis between the aggregated average values of pruning biomass production ratio (t d.m. ha^{-1}) and agro-climatic variables.

Crop	Parameter	ϱ Spearman	Confidence (*p*-Value) [1]
Vineyard	ACP_ab	0.636	*
	Ecocrop (Wclim)	0.768	**
	Ecocrop (ccm)	0.661	*
Olive	Koeppen climate	0.418	n.s.
	Ecocrop (Wclim)	0.395	n.s.

[1] Were reported, * $p < 0.05$ and ** $p < 0.001$ probability levels. n.s. not significant.

Table 7. Regression model for Ecocrop and the grid-cell average biomass production ratio for vineyard.

R	R^2	Standard Error
0.814	0.662	0.323
F Value	**Sig**	**Durbin-Watson**
15.665	0.04	2.45
Regression Model		
Y = Bo + B1 x X Bo = 0.534; B1 = 0.023 Biomass = 0.534 + 0.023xEcocrop (Wclim)		

For vineyards, the regression model provides a good fitting, with $R^2 = 0.662$, meaning that the linear model explains 66% of the variability in the quantity of biomass produced. This is a good value, considered the high variability and scale of the work done. It is also a limited result, since the sample size is only 10 points. The absolute standard errors are 0.323 t d.m. ha^{-1}, which represent the error for the prediction obtained by using the linear model. The model confidence is not fully accomplished (sig = 0.04), even though this is quite within the limit to be accepted as statistically of confident. Independence is accomplished according to the Durbin-Watson statistical analysis. Heteroscedasticity was also accomplished (scatter plot of standard residues and the forecasted values did not show any tendency). The standard residues do not follow a normal distribution. Consequently, the regression model obtained fulfils only partly the hypothesis for being consistent. Hence, the regression analysis results should be taken with caution.

Another regression model has been built for olives in relation to Ecocrop variable. Following the discussion for the previous regression model, the results should be taken with caution for the regression model obtained.

Table 8. Regression model for Ecocrop (Wclim) and the grid-cell average biomass production ratio for olive.

R	R2	Standard Error
0.610	0.294	1.26
F Value	**Sig**	**Durbin-Watson**
4.79	0.06	1.51
Regression Model		
Y = Bo + B1 x X Bo = −1.024; B1 = 0.074 Biomass = −1.024 + 0.074xEcocrop (Wclim)		

Both regression models improve the results that were obtained by the implementation of regressions to the complete database without averaging by climatic grid-cell. Therefore, it has been considered that for implementing correlations with agro-climatic data, the use of the equations presented in Tables 7 and 8 are very relevant.

In order to calculate the average ratios for pruning residues, the previous linear regression equations have been utilized to create ramp functions. The aim is to avoid extrapolation and projections out of the values predicted by the sample. Ramp function has been defined on the base of the lower and upper thresholds, defined by the values of the regression equation for low and upper values of the Ecocrop value for the sample (Table 9).

Table 9. Lower and upper thresholds utilized to build a ramp function.

Crop	Agroclimatic Variable (X Axis)	ECOL Lower Threshold (X; Y)	ECOU Upper Threshold (X; Y)	Equation
Vineyard Olive	Ecocrop	10; 0.764 20; 0.456	70; 2.14 60; 3.41	Y = 0.534 + 0.023 * X Y = −1.024 + 0.074 * X

3.4. Pruning Biomass Potential for Vineyard and Olive

The average ratios have been applied in order to assess the pruning biomass potential in Italy for vineyards and olive trees. According to 2011 agricultural area, as provided at NUTS-3 level by ISTAT (The National Institute for Statistics (ISTAT) is the main supplier of official statistical information in Italy), it was assessed that there is a biomass potential of about 845 kt d.m. y^{-1} from vineyard pruning and about 2600 kt d.m. y^{-1} from olive tree pruning.

These results are not consistent with the most recent evaluations performed in Italy (Table 10). In fact, EuroPruning assessment underestimates by 41% the vineyard pruning potential in comparison to the result found by Colonna et al. in 2013 [9], and by 25% the findings of the ENAMA (Italian National Agency for Agricultural Mechanization) study [55]. However, concerning olive tree pruning, the EuroPruning potential is higher than the results of the mentioned studies (respectively by 29% and 68%).

On the other hand, the same Italian studies differ with each other in the results, that are on average 30% higher in the Colonna study for both crops in comparison to the ENAMA results. In this case, beyond the different reference years, they differ mainly in methodology. The Colonna study is based on residue to product ratios (RPR), adopting the methodology developed in 1994 by AIGR and ENEA [56], while the ENAMA study is based on RSR, according to values proposed by Di Blasi et al. in 1997 [57].

Therefore, the EuroPruning results, not in line with the mentioned studies, should not be considered as a failure of the approach, but rather as the result of a different methodology.

In fact, as highlighted by the EU projects BEE and CEUBIOM, biomass assessment is a task performed with a wide range of approaches, methodologies, assumptions and datasets that lead to different estimates.

Nonetheless, a bigger number of direct observations on the field could improve the strength of correlation and the accuracy of the estimation in order to have stronger results.

Table 10. Pruning potential assessed by EuroPruning, compared with two recent studies in Italy.

Study	Reference Year	Vineyard (kt d.m. year^{-1})	Olive (kt d.m. year^{-1})
Colonna et al., 2013	2011	1436.8	2018.2
ENAMA, 2012	average 2006–2009	1123.4	1547.7
EuroPruning	2011	845.5	2607.3

4. Conclusions

Surveys and literature reviews have shown a high variability and large number of factors influencing the pruning biomass yield. The size of the database allowed a correlation analysis only for vineyards, olives and pome fruits. The analysis has not found good correlations with field variables like density or training system. Agro-climatic variables added from GIS databases have shown some better correlation.

Among the agro-climatic variable, the Ecocrop index gives the best correlation, allowing two regression models for vineyards and olive trees to be built. Pruning biomass ratios for the whole of the Italian territory have been computed according to these equations and utilized to assess pruning potential. The results are quite different from recent evaluations done in Italy, but the approach itself, similar to the one utilized for the assessment of herbaceous residues by other authors, is valid.

There are definite aspects that could be improved, namely the dimension of the sample and the reliability of the database. Exploring the existing literature and carrying out surveys is not enough to find strong correlations. Future methods for better assessments should be established from direct observation and measures in the field.

Supplementary Materials: The following is available online at http://www.mdpi.com/1996-1073/11/6/1365/s1, Table S1: Full set of record.

Author Contributions: D.G.G. conceived and designed the research; D.G.G., V.A. and A.S. performed the research; D.G.G., V.A. and E.S. analyzed the data; L.P. contributed materials/analysis tools; V.A. and D.G.G. wrote the paper.

Acknowledgments: This work was supported by the EuroPruning Project ("Development and implementation of a new and non existent logistics chain for biomass from pruning"), co-financed by the European Union under the Seventh Framework Programme (FP7) and by the Project SUSCACE (SUpporto Scientifico alla Conversione Agricola alle Colture Energetiche), MIPAAF, D.M. 2419 of 20/02/2008.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Scarlat, N.; Dallemand, J.F.; Monforti-Ferrario, F.; Banja, M.; Motola, V. Renewable energy policy framework and bioenergy contribution in the European Union—An overview from National Renewable Energy Action Plans and Progress Reports. *Renew. Sustain. Energy Rev.* **2015**, *51*, 969–985. [CrossRef]
2. IEA Bioenergy Task 42. BioEconomy Survey 2014. National BioEconomy Strategies IEA Bioenergy Implementing Agreement Countries. Available online: http://task42.ieabioenergy.com/ (accessed on 23 May 2018).
3. European Parliament Resolution of 2 July 2013 on Innovating for Sustainable Growth: A Bioeconomy for Europe. 2012/2295(INI). Available online: http://www.europarl.europa.eu/sides/getDoc.do?pubRef=-/ /EP//TEXT+TA+P7-TA-2013-0302+0+DOC+XML+V0//EN (accessed on 23 May 2018).
4. Bundschuh, J.; Chen, G. (Eds.) *Sustainable Energy Solutions in Agriculture*; CRC Press: Rome, Italy, 2018; ISBN 9781138001183.
5. Scarlat, N.; Dallemand, J.F.; Monforti-Ferrario, F.; Nita, V. The role of biomass and bioenergy in a future bioeconomy: Policies and facts. *Environ. Dev.* **2015**, *15*, 3–34. [CrossRef]
6. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the Promotion of the Use of Energy from Renewable Sources and Amending and Subsequently Repealing Directives 2001/77/EC and 2003/30/EC. Available online: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri= celex%3A32009L0028 (accessed on 23 May 2018).
7. FAO. The role of wood energy in Europe and OECD. In *Wood Energy Today for Tomorrow*; FAO, Forestry Department: Rome, Italy, 1997.
8. García-Galindo, D.; Cay Villa-Ceballos, F.; Vila-Villarroel, L.; Pueyo, E.; Sebastián, F. Seeking for Ratios and Correlations from Field data for Improving Biomass Assessments for Agricultural Pruning in Europe. Method and Results. In Proceedings of the 24th European Biomass Conference and Exhibition, Amsterdam, The Netherlands, 6–9 June 2016.
9. Colonna, N.; Macrì, A.; Regina, P. I Sottoprodotti Legnosi ed Erbacei del Settore Agricolo Italiano. In Proceedings of the Conference I Sottoprodotti Agroforestali e Industriali a Base Rinnovabile, Università Politecnica delle Marche, Ancona, Italy, 26–27 September 2013.
10. Vis, M.W.; van den Berg, D. Harmonization of biomass resource assessments. Volume I. Best Practices and Methods Handbook, Bee Project. *Tech. Rep.* **2010**. [CrossRef]
11. Garcia-Galindo, D.; Pascual, J.; Asín, J.; García-martín, A. Variability and Confidence Interval in the Estimation of Agricultural Residual Biomass at a Municipality Level in Teruel Province (Spain). In Proceedings of the 15th European Biomass Conference and Exhibition, Berlin, Germany, 7–11 May 2007.
12. Garcìa-Galindo, D.; Gòmez-Palmero, M.E.P.; Germer, S.; Pari, L.; Alfano, V.; Dyjakon, A.; Sagarna, J.; Rivera, S.; Poutrin, C. Agricultural Pruning as Biomass Resource: Generation, Potentials and Current Fates. An approach to its state in Europe. In Proceedings of the 24th European Biomass Conference and Exhibition, Amsterdam, The Netherlands, 6–9 June 2016; pp. 1579–1595.
13. Caruso, T.; Proietti, P. Modelli d'impianto, Forme di Allevamento e Criteri di Potatura per la Nuova

Olivicoltura. 2011. Available online: http://dspace.unitus.it/dspace/handle/2067/2600 (accessed on 23 May 2018).

14. Tous, J. Olive planting systems and mechanization. *Olivebioteq* **2014**, *181*. [CrossRef]
15. Jones, H.G. How do rootstocks control shoot water relations? *New Phytol.* **2012**, *194*, 301–303. [CrossRef] [PubMed]
16. Warschefsky, E.J.; Klein, L.L.; Frank, M.H.; Chitwood, D.H.; Londo, J.P.; von Wettberg, E.J.; Miller, A.J. Rootstocks: Diversity, domestication, and impacts on shoot phenotypes. *Trends Plant Sci.* **2016**, *21*, 418–437. [CrossRef] [PubMed]
17. Webster, A.D. Rootstock and interstock effects on deciduous fruit tree vigour, precocity, and yield productivity. *N. Z. J. Crop Hortic. Sci.* **1995**, *23*, 373–382. [CrossRef]
18. Gregory, P.J.; Atkinson, C.J.; Bengough, A.G.; Else, M.A.; Fernández-Fernández, F.; Harrison, R.J.; Schmidt, S. Contributions of roots and rootstocks to sustainable, intensified crop production. *J. Exp. Bot.* **2013**, *64*, 1209–1222. [CrossRef] [PubMed]
19. Di Vaio, C.; Marra, F.P.; Scaglione, G.; La Mantia, M.; Caruso, T. The effect of different vigour olive clones on growth, dry matter partitioning and gas exchange under water deficit. *Sci. Hortic.* **2012**, *134*, 72–78. [CrossRef]
20. Nardini, A.; Gascó, A.; Raimondo, F.; Gortan, E.; Lo Gullo, M.A.; Caruso, T.; Salleo, S. Is rootstock-induced dwarfing in olive an effect of reduced plant hydraulic efficiency? *Tree Physiol.* **2006**, *26*, 1137–1144. [CrossRef] [PubMed]
21. Rugini, E.; De Pace, C.; Gutiérrez-Pesce, P.; Muleo, R. Olea. In *Wild Crop Relatives: Genomic and Breeding Resources*; Springer: Berlin/Heidelberg, Germany, 2011; pp. 79–117.
22. Corso, M.; Bonghi, C. Grapevine rootstock effects on abiotic stress tolerance. *Plant Sci. Today* **2014**, *1*, 108–113. [CrossRef]
23. Granett, J.; Walker, M.A.; Kocsis, L.; Omer, A.D. Biology and management of grape phylloxera. *Annu. Rev. Entomol.* **2001**, *46*, 387–412. [CrossRef] [PubMed]
24. Serra, I.; Strever, A.; Myburgh, P.A.; Deloire, A. The interaction between rootstocks and cultivars (*Vitis vinifera* L.) to enhance drought tolerance in grapevine. *Aust. J. Grape Wine Res.* **2014**, *20*, 1–14. [CrossRef]
25. Tramontini, S.; Vitali, M.; Centioni, L.; Schubert, A.; Lovisolo, C. Rootstock control of scion response to water stress in grapevine. *Environ. Exp. Bot.* **2013**, *93*, 20–26. [CrossRef]
26. Garcìa-Galindo, D.; López, E.; Gomez, M.; Sebastián, F.; Gebresenbet, G.; Jirjis, R.; Kern, J.; Germer, S.; Pari, L.; Suardi, A.; et al. EuroPruning Project: Summary of Final Results. In Proceedings of the 24th European Biomass Conference and Exhibition, Amsterdam, The Netherlands, 6–9 June 2016.
27. Velázquez-Martí, B.; Fernández-González, E. Analysis of the process of biomass harvesting with collecting chippers fed by pick up headers in plantations of olive trees. *Biosyst. Eng.* **2009**, *104*, 184–190. [CrossRef]
28. Velázquez-Martí, B.; Fernández-González, E.; López-Cortés, I.; Salazar-Hernández, D.M. Quantification of the residual biomass obtained from pruning of vineyards in Mediterranean area. *Biomass Bioenergy* **2011**, *35*, 3453–3464. [CrossRef]
29. Velázquez-Martí, B.; López-Cortés, I.; Salazar-Hernández, D.M. Dendrometric analysis of olive trees for wood biomass quantification in Mediterranean orchards. *Agrofor. Syst.* **2014**, *88*, 755–767. [CrossRef]
30. Scarlat, N.; Blujdea, V.; Dallemand, J.F. Assessment of the availability of agricultural and forest residues for bioenergy production in Romania. *Biomass Bioenergy* **2011**, *35*, 1995–2005. [CrossRef]
31. Scarlat, N.; Martinov, M.; Dallemand, J.F. Assessment of the availability of agricultural crop residues in the European Union: Potential and limitations for bioenergy use. *Waste Manag.* **2010**, *30*, 1889–1897. [CrossRef] [PubMed]
32. Monforti, F.; Bódis, K.; Scarlat, N.; Dallemand, J.F. The possible contribution of agricultural crop residues to renewable energy targets in Europe: A spatially explicit study. *Renew Sustain. Energy Rev.* **2013**, *19*, 666–677. [CrossRef]
33. ANPA. I Rifiuti del Comparto Agroalimentare. Rapporti 11/2001. 2011. Available online: http://www.apat.gov.it/site/_contentfiles/00038200/38230_Rapporti_01_11.pdf (accessed on 23 May 2018).
34. Pantaleo, A.; Carone, M.T.; Pellerano, A. Olive residues to energy chains in the Apulia region. Part I. Financial appraisal of energy conversion routes. *J. Agric. Eng.* **2009**, *1*, 37–47.
35. Motola, V.; Colonna, N.; Alfano, V.; Gaeta, M.; Sasso, S.; De Luca, V.; De Angelis, C.; Soda, A.; Braccio, G. Censimento Potenziale Energetico Biomasse, Metodo Indagine, Atlante Biomasse su WEB-GIS. Report ENEA—Ricerca Sistema Elettrico, RSE/2009/167. Available online: http://editors.enea.it/it/Ricerca_sviluppo/ documenti/ricerca-di-sistema-elettrico/censimento-biomasse/rse167.pdf (accessed on 23 May 2018).

36. IIASA/FAO. Global Agro-Ecologycal Zones (GAEZ v3.0). IIASA (Laxenburg, Austria) and FAO. 2012. Available online: http://www.gaez.iiasa.ac.at (accessed on 23 May 2018).
37. CGIAR. Ecocrop Database. CGIAR Consortium of International Agricultural Research Centers. 2012. Available online: http://gisweb.ciat.cgiar.org/ClimateChange/EcoCropFB (accessed on 23 May 2018).
38. Kottek, M.; Grieser, J.; Beck, C.; Rudolf, B.; Rubel, F. World Map of the Köppen-Geiger climate classification updated. *Meteorol. Z.* **2006**, *15*, 259–263. [CrossRef]
39. Spinelli, R.; Magagnotti, N.; Nati, C. Harvesting vineyard pruning residues for energy use. *Biosyst. Eng.* **2009**, *105*, 316–322. [CrossRef]
40. Spinelli, R.; Picchi, G. Industrial harvesting of olive tree pruning residue for energy biomass. *Bioresour. Technol.* **2010**, *101*, 730–735. [CrossRef] [PubMed]
41. Spinelli, R.; Nati, C.; Pari, L.; Mescalchin, E.; Magagnotti, N. Production and quality of biomass fuels from mechanized collection and processing of vineyard pruning residues. *Appl. Energy* **2012**, *89*, 374–379. [CrossRef]
42. Magagnotti, N.; Pari, L.; Picchi, G.; Spinelli, R. Technology alternatives for tapping the pruning residue resource. *Bioresour. Technol.* **2013**, *128*, 697–702. [CrossRef] [PubMed]
43. Silvestri, S.; Cristoforetti, A.; Mescalchin, E.; Spinelli, R. Recovery of Pruning Waste for Energy Use: Agronomic, Economic and Ecological Aspects. In Proceedings of the Central European Biomass Conference, Graz, Austria, 26–29 January 2011.
44. Recchia, L.; Daou, M.; Rimediotti, M.; Cini, E.; Vieri, M. New shredding machine for recycling pruning residuals. *Biomass Bioenergy* **2009**, *33*, 149–154. [CrossRef]
45. Cotana, S.; Cavalaglio, G. Recovery of Vineyards Pruning Residues in an Agro-Energetic Chain. In Proceedings of the 15th European Biomass Conference and Exhibition, Berlin, Germany, 7–11 May 2007.
46. Spinelli, R.; Magagnotti, N.; Nati, C.; Cantini, C.; Sani, G.; Picchi, G.; Biocca, M. Integrating olive grove maintenance and energy biomass recovery with a single-pass pruning and harvesting machine. *Biomass Bioenergy* **2011**, *35*, 808–813. [CrossRef]
47. Acampora, A.; Croce, S.; Assirelli, S.; Del Giudice, A.; Suardi, A.; Spinelli, R.; Pari, L. Product contamination and harvesting losses from mechanized recovery of olive tree pruning residues for energy use. *Renew. Energy* **2013**, *53*, 350–353. [CrossRef]
48. Libutti, A.; Garofalo, P.; Rovas, D.; Zabniotou, A.; Monteleone, M. Management of Pruning Residues for both Renewable Energy and Soil Fertility. In Proceedings of the 22nd European Biomass Conference and Exhibition, Hamburg, Germany, 23–26 June 2014.
49. Moscatello, S.; Proietti, S.; Baldicchi, A.; La Cara, F.; Famiani, F.; Battistelli, A. Vitis Pruning Material: Variability in Quantity and Quality of the Lignocellulosic Material Among 42 Varieties Cultivated in Italy. In Proceedings of the 19th European Biomass Conference and Exhibition, Berlin, Germany, 6–10 June 2011.
50. Boschiero, M.; Neri, P.; Kelderer, M.; Zerbe, S. Apple Orchard's Woody Residues as a Potential Bioenergy Source: A LCA Case Study in South Tyrol (Italy). In Proceedings of the 21st European Biomass Conference and Exhibition, Copenhagen, Denmark, 3–7 June 2013.
51. Prando, D.; Boschiero, M.; Campana, D.; Gallo, R.; Baratieri, M.; Comiti, F.; Mazzetto, F.; Zerbe, S. Woody Biomass in South Tyrol: Feedstock Availability and Characterization of Different Conversion Processes for Energy Production. In Proceedings of the 22nd European Biomass Conference and Exhibition, Hamburg, Germany, 23–26 June 2014.
52. Trabucco, A.; Zomer, R.J. Global Aridity Index (Global-Aridity) and Global Potential Evapo-Transpiration (Global-PET) Geospatial Database. CGIAR Consortium for Spatial Information. 2009. Available online: http://www.csi.cgiar.org (accessed on 23 May 2018).
53. EEA. The Biogeographical Regions Dataset. European Environment Agency. 2011. Available online: http://www.eea.europa.eu/data-and-maps/data/biogeographical-regions-europe (accessed on 23 May 2018).
54. Cohen, J. *Statistical Power Analysis for the Behavioral Sciences*, 2nd ed.; Lawrence Erlbaum: New York, NY, USA, 1988.
55. AA.VV. Studio conclusivo "Progetto Biomasse ENAMA". Parte 1—Biomasse ed Energia. Capitolo 2—Disponibilità Delle Biomasse, ENAMA—MiPAAF. 2012. Available online: http://www.progettobiomasse. it/it/studio.php (accessed on 23 May 2018).
56. A.I.G.R. (Associazione Italiana di Genio Rurale). *Potenzialità energetica da biomasse nelle regioni italiane*; Rapporto conclusivo, Contratto A.I.G.R.—ENEA del 03 dicembre 1992—Pratica 00073; A.I.G.R.: Roma, Italy, 1994.

57. Di Blasi, C.;Tanzi, V.; Lanzetta, M. A study on the production of agricultural residues in Italy. *Biomass Bioenergy* **1997**, *12*, 321–331. [CrossRef]

Biomass and Bioenergy 107 (2017) 398e410

Contents lists available

Biomass and Bioenergy

journal http://www.elsevier.com/locatee/biomb

Review

Current and innovative technologies for pruning harvesting: A review

L. Pari [a], A. Suardi [a, *], E. Santangelo [a], D. García-Galindo [b], A. Scarfone [a], V. Alfano [a]

[a] CREA Research Centre for Engineering and Agro-Food Processing, Monterotondo, RM, Italy
[b] CIRCE Research Centre for Energy Resources and Consumption, Zaragoza, Spain

a r t i c l e i n f o

Article history:
Received 27 April 2017
Received in revised form
19 August 2017
Accepted 22 September 2017 Available
online 4 October 2017

Keywords:
Harvest pruning
Shredder
Baler
Chipper
Agricultural residues
Mechanization

a b s t r a c t

Pruning residues can provide a significant amount of biomass despite being rarely used as a renewable sources to replace fossil fuels. Exploiting such residues entails creating a sustainable and cost-effective supply chain in which the harvesting and initial processing of the residues play a crucial role. The study is a detailed and accurate survey of the harvesting technologies available in Europe for harvest pruning. After defining the main harvest technologies and the distribution of manufacturers in Europe, the survey details the main groups of implements: shredders, chippers and balers. For each group, the most important configurations are discussed, together with the main characteristics of the machine. Some of the main innovations are detailed (modular machines, non-stop balers, densification of the biomass) which can improve the quality of the product and the economic sustainability of the chain.

Contents

E-mail address: alessandro.suardi@crea.gov.it (A. Suardi). https://doi.org/10.1016/j.biombioe.2017.09.014 0961-9534/

1. Introduction

Residues of permanent crops in Europe are a substantial reservoir of renewable biomass for energy and industrial use. The 10.6 Mha currently covered by permanent crops generate 13 Tg

(oven-dry basis) of pruning. However, the rational use of this biomass source is being hindered [1,2]. Firstly by an increase in surfaces, and a conversion from traditional to intensive systems is forecast as well as a growing demand for fuel biomass [1,3e5]. Secondly, there are various barriers tied to the use of prunings and the development of a sustainable logistic chain to produce energy from it [6,7].

Pruning (branches and shoots of fruit trees) is considered a problem rather than an opportunity and, hence, it is not used or incorrectly disposed of [8].

Environmental concerns regarding the use of fossil fuel and their depletion have boosted a cultural change in the sustainable use of renewable sources. As a result, the formulation of more strict regulations regarding pruning in most European countries [2] has led to a renewed interest in pruning recovery. Over the last fifteen years several scholars have identified cost-effective technologies for harvesting, processing and delivering pruning residues. In fact, harvesting is a key stage that influences the product quality, the type of logistics chain and the economic sustainability of the pruning supply chain. In reality, over the years, many machine manufacturers have developed dedicated implements for collecting pruning residues [9e14].

Equipment that facilitates the harvesting and processing of agricultural pruning is already available on the market and many manufacturers offer different models that are tailored to specific harvesting chains. The aim of the present work is to provide a thorough overview of the technologies available for harvest pruning, from basic equipment to the state of the art.

2. Pruning collection and fuel quality

The source of the biomass as well as the techniques employed during the supply chain affect the quality of woody biomass. Apart from aspects related to biomass properties (such as moisture, ash, foliage content, and chemical composition), comminution and storage have a strong influence on other important parameters such as the presence of contaminants (soil, stones), particle size and bulk density, which may impact on the quality of the biomass. Comminution is exploited for baling, where the benefit of a more stable and prolonged storage period is diminished by the cost of this extra step.

Biomass losses and contamination are directly related to the regulation of the pick-up device. Low-lying pick up mechanisms help to reduce losses, but increase the inlet of soil particles, to the detriment of fuel quality [15]. The ash content of the shredded material has been reported to be higher than the branch material collected directly from the trees, and the ash are also responsible for a reduction in the heating value as well as a number of serious power plant problems through slagging, corrosion and fouling [16].

Biomass losses can be also a consequence of the working width of the machine and the lack of suitable windrowing. As hypothesized by Acampora et al. [15] the mismatch between windrow width and machine working width can lead to a high loss of biomass, but with voluminous pruning, such as those of olive orchards, building a narrow windrow can be arduous. Losses can also increase when the height of the pick-up is raised excessively in order to prevent soil contamination.

The shape, size, number and type of chipping devices, and the machine settings can greatly alter the feedstock quality [17e19]. An incorrect comminution, can lead to serious problems with the wood fuel such as high dry matter losses, high ash content, reduction in energy value, and self-ignition [20]. The particle size distribution of woody biomass plays a pivotal role in producing a high-grade fuel, because it directly influences the bulk density, the storage behavior, and the transport costs, and it can also create problems in the fuel feeding at the heating plant. The particle size is fundamentally determined by the machine design and settings, and can be a benchmark of the machine performance in terms of product quality [21]. Using the wrong machine can lead to unevensized chips with a high proportion of oversized or undersized particles, and any attempt to decrease one class may result in an undesirable increase in the other, even when refining devices are used [13,15,22].

Beside the particle size, the comminution of pruning must take into account the morphology of the wood pieces. The most commonly-used shredders produce wood particles with de-fibered ends unlike the homogeneous pieces resulting from chipping. This difference has significant implications during storage because the unclean cut of the shredders can cause the biomass to be more prone to degradation and fermentation. All types of biological and chemical changes in wood fuels during storage and drying leads to changes in fuel properties. However, the use of a chipper may also lead to a lower chip quality. This has been observed in the wood energy chain where the wear of the knife alters the chip quality and the productivity of the machine [22]. When the knives are not sharp, the chipper tends to break the wood rather than cutting it, thus producing finer and oversized wood particles [22].

The role of quality becomes more pronounced as the supply system varies in different countries and in different plant systems. An important goal of quality control is to reduce quality variations and as much as possible to obtain a homogeneous product [16,19].

3. Pruning management

3.1. Traditional handling

The pruning stage produces branches, shoots and buds which are then left in the field. In several areas of Europe is the biggest pieces of wood pruning are used for firewood. Farmers usually obtain firewood pieces from thick branches, with a diameter larger than 50 mm [14]. They perform the cut with chainsaws and gather the firewood manually or with a trailer and then put it at the side of fields. Pruning used for firewood is mainly carried out in small plantations, for self-consumption, or for local markets.

Due to the lack of a well organized pruning biomass supply chain in Europe, there is no real market for pruning residues (<50 mm). Thus small branches and shoots that have been pruned and left on the ground are usually not collected, chipped and used for energy production (excluding rare cases), but usually are disposed of by farmers in two ways:

1. they are removed from the orchard, and then piled and disposedof or piled and burned at the side of the field;
2. they are mulched and left/incorporated on/into the soil.

The branch removal phase is usually carried out by a tractor equipped with a fork or similar device which pushes the pruned branches down the rows until the edge of the field.

Pruning can be also left on the soil after mulching. Hammer mulchers (also known as hammer mowers or simply mulchers) are usually used to comminute the dendromass into small pieces. These machines are mounted on the back of the tractor on a threepoint hitch and are supplied with the power take-off (PTO) of the tractor.

In rare cases, prunings with a small diameter can also be recovered for energy purposes using specific machines that chip, shred or bale the dendromass so that it can be transported, stored and used in specific boilers mainly for heat production.

3.2. Rational use of the pruning: harvesting technology

A more environmentally sustainable use of pruning is increasingly being proposed to replace open-air burning [2,5,14]. In addition, driven by the increasing biomass demand [3,4] and the potential amount of dry matter obtainable by pruning, various European projects have focused on organizing and implementing pruning supply chains for energy production [23e26].

Harvest pruning generally requires one or two passes [7]. The difference is determined by the need for windrowing the branches to facilitate collection and minimize biomass losses. If branches and shoots are spread in the interrows during pruning, there needs to be an initial pass for the mechanical windrowing and then a second one for the harvesting. Pruning rakes are machines that guide the pruned branches into the middle of the row thereby making shredding or cleaning easier. These tools are driven by the PTO shaft of the tractor, and are composed of sweeping rotors made of steel spring tines that can be used in different kinds of orchard whatever the ground. These types of equipments can work at high speeds (5e7 km h^1) but they require a double pass per row, i.e. in both directions, in order to create a pruning windrow. Otherwise, a higher degree of integration can be achieved when the same tractor is equipped with a harvester and a windrower, enabling the biomass to be collected in one pass. This system may be composed of a sweeping rotor (usually two made with flexible, but highly resistant plastic bars) mounted at the front of the tractor and powered by hydraulic engines. Using the hydraulic system, it is usually possible to adjust the distance between the rotors.

Some pruning harvesters can be equipped with two hydraulic swath brushes mounted on both sides of the pick-up roll in order to extend the machine's collecting capacity. In our personal experience, this last system is more suited to compact windrows that already exist, although its results are not very effective for all types of pruning.

To sum up, the supply chain considered suitable for harvest pruning consists of windrowing which can be done either separately or then integrated with biomass processing. In this second step, the pruning is handled by shredders, chippers or balers. All the possible configurations are listed in Table 1.

Within the framework of the EuroPruning project [1,23], a thorough analysis of the machines available on the European market for harvest pruning revealed that shredding is currently the most common technology (Table 2). Out of a total of 75 commercial models, 60 are adaptations of conventional mulchers, with different degrees of innovation and integration for improving the harvest pruning biomass. Chippers still lack sufficient development and penetration in the sector, although they are essential whenever the product needs to be compatible with consumers of regular woodchips. Around 78% of the models are built in Italy and Spain (Fig. 1) and the figure reaches 86% including France. These data are easily explained taking into account that in the EU28, Spain, Italy and France account for the largest areas dedicated to permanent crops (more than 7 Mha) [1,2].

3.3. **Shredders**

Pruning shredders break the branches down into pieces using a horizontal shaft powered by the tractor's PTO and by mounting elements with blunt (hammers) or sharp (knives) blades. Shredding is a mature technology and the number of commercial machines is increasing (Table 2). Over the years, machine manufacturers have adapted the original implements from the incorporation of the pruning into the soil after processing as organic substrate to its collection in trailers using a blower or with built-in bins [5,9]. The general innovation with respect to conventional mulchers consists in the improvement in the pick-up for pruning collection, and the conveying system to a trailer. From a mechanical point of view, the working principles are very similar, and they are in, for example, the number of teeth on the pick-up device, or the hammers on the shredders, as well as the type of discharge or the use of trailers or bins and their capacity [9,27].

Shredders are usually coupled to the PTO of the tractor and can be mounted both in front or at the rear (depending on the model). Usually, the majority of models are mounted at the rear of the tractor which passes over the pruning left in windrows on the soil. Thus, the tractor may require additional protection to prevent damage to the electrical or hydraulic systems located underneath the tractor body if voluminous windrows and thick branches are present. Some shredders are mounted at the rear of the tractor but entail the tractor being driven in reverse (e.g. Jordan RH25).

Pruning shredders can be towed by a tractor ranging from 50 to 70 kW, but heavier industrial units applied to powerful farm tractors (150e200 kW) are being developed. The cost of the most common pruning shredder is relatively affordable (10,000e20,000 euros) and thus are commonly used by farmers and part-time contractors [5,14,15].

The main configurations adopted for pruning shredders can be summarized as (Table 1):

Windrowing plus harvest with shredder in front (M1). This is the most common method. Machinery manufacturers adapt a fan to convey the fine hog material through a duct towards a trailer towed by the tractor. The innovation is the fan and the conveying system.

Windrowing plus harvest with shredder at rear (M2). This system is also common. M2 and M3 differs just in terms of the position of the shredder (at the rear rather than in front), but the principle is the same. Beside the launcher duct to convey particles to a trailer, the machines are equipped with a pick-up. Sometimes particles are transferred by inertia, others require a fan.

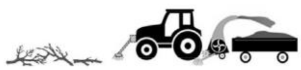
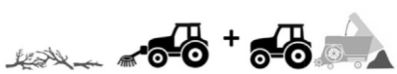
Windrowing plus harvest with rear shredder and bin (M3). There are several M3 models on the market, though not as many as with M2. This is because M3s have a portable bin to accumulate the biomass. Self-discharging bins allow for easy emptying, and sometimes the bin can be raised for discharge onto trailers or containers.

Windrowing plus harvest with rear shredder and big-bag (M4). There are only few models on the market. The big-bag solution facilitates an easy discharge in the middle of a row. However, it also entails collecting the big bags from the plantation at a later stage than with the other systems. The quality of the material may improve, but the large-scale logistics with big bags could be not affordable considering the high cost of each single bag (untill 10V/big-bag) and the difficult product discharging at the plant.

Integrated windrowing and harvest with rear shredder (M5). Similarly to M2. In this case the rear shredder incorporates a windrowing system, allowing a one-pass collection. The windrower can also be mounted at the front of the tractor. Integrated windrowing and harvest with rear shredder and bin (M6). Similar to M3 but with the integration incorporated in M5. Integrated windrowing and harvest with rear shredder and bigbags (M7). Similar to M4 but with the integration incorporated in M5.

Pruning shredders have been extensively tested on Mediterranean crops such as olive orchards and vineyards [8,9,13e15,20,27,28], but experimental evidence has also been increasing for fruit orchards and kiwifruit [5,9]. The variability of technical parameters (working width, harvesting speed, container

Table 1
Summary of implements for shredders/chippers, balers and integrated systems for pruning and harvesting.

Tech	Figure	Code	Description
Shredders and shredders		[M1]	Windrowing þ harvest with shredder in front
		[M2]	Windrowing þ harvest with shredder at rear
		[M3]	Windrowing þ harvest with rear shredder and bin
		[M4]	Windrowing þ harvest with rear shredder and big-bag
		[M5]	Integrated windrowing and harvest with rear shredder
		[M6]	Integrated windrowing and harvest with rear shredder and bin
		[M7]	Integrated windrowing and harvest with rear shredder and big-bags
Chippers		[CH1]	Windrowing þ harvest with chipper in front
		[CH2]	Windrowing þ harvest with rear chipper and bin
		[CH3]	Integrated windrowing and harvest with rear chipper and bin
		[CH4]	Integrated windrowing and harvest with rear chipper and big-bags
		[CH5]	Automotive chipper with rear trailer
Balers		[BL1]	Windrowing þ harvest with standard hay baler
		[BL2]	Windrowing þ harvest with rear baler
		[BL3]	Integrated windrowing and harvest with rear baler
		[BL4]	Windrowing þ harvest with front-mini-baler
Integrated pruning and harvest		[PP1]	Pre-pruning integrated with collection and shredding/chipping
		[PP2]	Pre-pruning integrated with collection and shredding/chipping in an automotive machine

capacity) and field conditions (species, layout, type of plantation, amount of pruning) lead to a varied performance and unit cost. Although significant productivity gains have been obtained in the last few years, the cost can still vary between V11 and V60 per green-tone, including the extraction, regardless the specie [9].

Despite the similar working principle, the quality of product in terms of particle size distribution is variable [13,15,29]. Rather than being comparable with forestry woodchips, the product is similar to a hog material made of broken and de fibered parts of branches. The particle size can vary considerably depending on the shredder. Comparing eleven shredders in vineyard pruning, Spinelli et al. [13] reported an exceedingly large proportion of oversized and/or

Table 2
Summary of harvesting machineries available in Europe (and Canada).

Manufacturer	Country	Models			Integral pre-prunners
		Shredders	Chippers	Balers	
Anderson	Canada			1	
Concept Machines Bernhardt (CMB)	France	1			
Jonues i fills	France	2			
Oonyx	France	1			
Sousliskoff	France	2			
Jordan	Germany		1		
Kuhn	Germany	2			
Stoll	Germany	1			
Fotopoulos	Greece	1			
Berti	Italy	4			
Caeb	Italy			1	
Costruzioni Nazzareno	Italy		2		
Dragone	Italy	1			
Facma	Italy	1			
Falc	Italy	3			
Favaretto Paolo	Italy				1
Lerda	Italy			2	
Nobili	Italy	2			
Omarv	Italy	2			
Omat	Italy	1			
ONG	Italy		1		
Orsi	Italy	1			
Peruzzo	Italy	2	1		
Rinieri	Italy	2			
Seppi	Italy	2			
Sgarbi	Italy	2			
Tierre	Italy		2		
Tigieffe	Italy			1	
Wolagri	Italy			1	
Forest Technology Centre	Poland	1			
Inventor	Poland	1			
Pimr	Poland			1	
Belafer	Spain	2			
Picursa	Spain	11			
Promagri	Spain	2			
Serrat	Spain	7		1	
Perfect (Van Wamel B.V.)	The Nederlands	1			
Lely	The Nederlands			1	
Total		58	7	9	1

undersized particles. The addition of refining devices, such as screens or counter-knives reduced the oversized particles but increased the finest ones. The imbalance between large and fine particles was also observed by Acampora et al. [15] in olive pruning with an uneven particle distribution among six shredder models. As a consequence, the use of this product in conventional facilities is constrained due to the problems of clogging which can be caused in the conveying and feeding to boilers. Therefore, an industrial, rather than domestic use appears to be the most suitable outlet market for this type of fuel [13,15].

3.4. **Chippers**

In the wood energy chain, the most common commercial machines are equipped with discs or drum chippers [17]. In both cases the biomass is forced to go through a blade (the disc or the blades held on the drum) and a counter-blade. The production of fuel with a suitable particle size distribution requires the installation of refining devices [22,30,31].

For pruning, residue chippers, in contrast to shredders, are relatively new option. A variety of numbers and shapes of knives are used by chippers to comminute the pruning. However, all the types of knives are vulnerable to all non-wood material, and consequently the cutting system itself can be damaged, for example, by dirt, stones and iron wires, thus negatively impacting on product quality, performance and the maintenance costs of the machine [22]. For this reason, an automatic flawlessly designed pick-up is thus critical to prevent stones and dirt from being accidentally thrown into the chipping system during the pruning comminution.

Chippers are produced as integrated systems or are built with bins (Table 1):

Windrowing plus harvest with chipper in front (CH1). Conceived for chipping energy crops or forestry residues, but suitable for pruning collection. The same implement as [M1] except for the improvement provided by the chipping system.

Windrowing plus harvest with rear chipper and bin (CH2). New models on the market. Operates like [M3], except for the chipping system (instead of a shredder).

Integrated windrowing and harvest with rear chipper and bin (CH3). There is only one model in Europe, which was developed as part of the Europruning project. It harvests chips in big bags or on rear trailers. Operates as described for [M4].

Integrated windrowing and harvest with rear chipper and big-bags (CH4). Same as [CH3], only one model available. Developed in Europruning project, allows harvesting with both [CH3] ad [CH4] options.

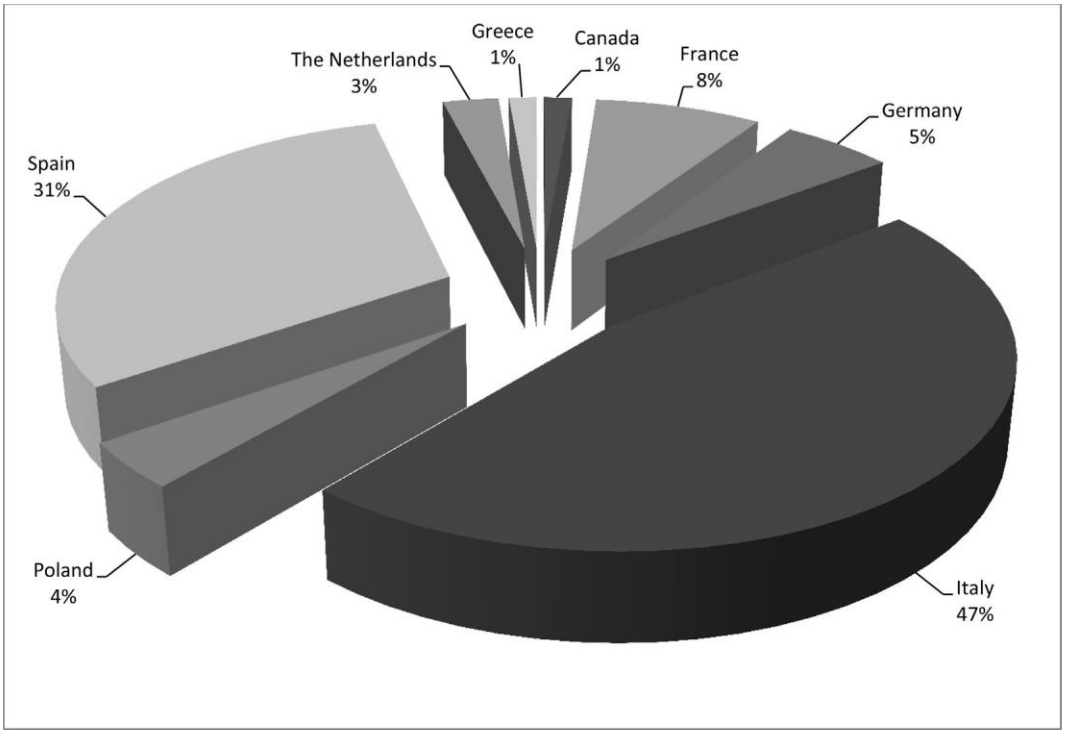


Fig. 1. Distribution of pruning harvesters model by country.

Automotive chipper with rear trailer (CH5). The only model surveyed (Table 1) that is no longer produced. Powerful and compact, but requires larger investment by farmers.

Chippers have been extensively used in forestry and in the cultivation of wood species for energy [17,21,22,32]. Chippers process the wood with sharp blades which enables the biomass to be cut in more homogeneous pieces [18,33]. The cuts are clean, and defibering is avoided. The type of material obtained is handled and stored more easily than the conventional hog material produced by shredders [20,34]. As fuel, the wood chips cause less problems when being fed to boilers, such as in screw feeders, silos or hoppers; both their domestic and industrial usage have been questioned [9]. Small-scale recovery is preferable for domestic consumption, however reservations remain regarding the quality, thus prompting interest in industrial units, derived from modified foragers or industrial chippers [35].

There are few pruning chippers on the market that can pick up and chip the biomass and that have different working configurations (Tables 2 and 3). Beside the design characteristics, the main element of these chippers is the comminution unit. Producing chips out of branches is a challenge firstly because the uneven shape and variable diameter of the branches makes it difficult to obtain regular sized chips. Manufacturers have tried to design chipping systems that ensure the production of uniform chips through a sharp cut in the wood and the minimum use of tractor power [36]. This should improve in the characteristics of the wood chip (avoiding frayed edges) and the particle size distribution, as observed for the ONG machine by Pari et al. [37] and Magagnotti et al. [9].

The ONG PC50 model [1] is an interesting attempt to develop a flexible machine that works in various logistic chains, discharging the product (particle size class P45, according to EN ISO 17225e4:2014) in big-bags, trailers or in a medium sized hoppers of 3.5 m^3 (Fig. 2). The JORDAN RH25 is an industrial unit designed to overcome the limits of lighter chippers (productive and the structural limits) [14]. RH25 has a disc chipper that permit to produce even-shaped particles and, hence, a high-grade fuel. Of cource, it is an industrial machine that calls for a rather intense utilization level to be cost-effective [14].

Pruning harvesters based on chipping systems produce more regular-sized chips that are similar to forest woodchips than those produced by shredders. The evolution of these technologies is therefore necessary to promote the agricultural pruning within the biomass market. New chipping models need to convince those that are accustomed to shredding technologies that they are reliable.

3.5. **Balers**

Dendromass can also be collected into bales. Baling entails reprocessing the bale by chipping, however it facilitates easier storage because, unlike chips, bales can be kept for months [35]. In fact, the results obtained during six months of pruning bales and wood pruning chip storage carried out as part of the Europruning project, highlighted that bales presented a better quality compared with the comminuted material [39]. The storage of stacked apple pruning bales in Germany and vineyard pruning bales in Spain showed a percentage variation in combustible matter after six months of 2.4% ± 0.64 and 0.0% ± 0.84, respectively, while the comminuted material stored in piles showed a variation between 3.1% and 7.8% [39]. In order to be used as fuel, after storage, the bales can be burned directly in boilers with various power ranges, and which can usually take either circular or cubed bales. Otherwise, the bales have to be comminuted by specific stationary or mobile shredders. This process can be carried out by stationary shredding machines at the plant, or with mixer wagons [40] in the field or at the plant.

The bales produced from hay can vary in shape (quadrangular or round) and size. However, the rationale of this work was to provide an overview of the collection systems where each implement was included, without detailing the mechanical aspects of each

Table 3
Main characteristics of pruning chipper.

Make	Model	Configuration (Table 1)	Comminuter type	Working width (mm)	Weight (kg)	Hopper capacity (m^3)	Min. Power (kW)	Max branch diameter (mm)	Productivity t h^1 (ha h^1)	Specie harvested
Costruzioni Nazzareno	Marev Alba 120	CH2	Knives mill	1200	e	1.2	70	40e80	e (0.3e1.1)[a]	Vitis vinifera, L.
	Marev Alba 150			1500	2800	1.5e2.4	70	40e80	1.99 (0.86)[d]	
	Marev Alba 180			1800	e	1.5e2.4	70	40e80	e (0.4e1.6)[a]	
	Marev Luce 150			1500	e	1.5	70	e	e (0.5e1.5)[b]	
	Marev Luce 180			1800	e			e		
	Marev Luce 200			2000	e			e		
ONG	PC50 (bigbag)	CH4	Auger mounting helicoidal blades	1560	2126	1.5	45	80	2.2 (0.7)[e]	Vitis vinifera, L.
Jordan	RH25	CH1	Disc chipper (single knife)	1750	2500	e	150	e e	2e7[f] ()	Olea europea, L.
Peruzzo	Cobra collina 1200	CH2	Shredding shaft with fixed teeth	1200	1400	1.3	37		2.4e3.2 (1.3 e1.8)[c]	Vitis vinifera, L.
	Cobra collina 1400		Shredding shaft with fixed teeth	1400	1500	1.5	44	e		Vitis vinifera, L.
	Cobra collina 1600		Shredding shaft with fixed teeth	1600	1650	1.8	51	e		Vitis vinifera, L.
Tierre	Plano	CH2	Rotor with removable knives	1600	3000	1.5e5.0	66	80	11.89 (0.85)[g]	Olea europea, L.
	Green Bee Jolly	CH2	Rotor with removable knives	1600	600	2.0	80	e	e	Vitis vinifera, L.
				1800	700	2.3	90	e	e	Vitis vinifera, L.
				2000	780	2.6	100	e	e	Vitis vinifera, L.

[a] Website of the machine manufacturer [66].
[b] Website of the machine manufacturer [67].
[c] Website of the machine manufacturer [68].
[d] [38].
[e] Own measurements (results of a field test carried out by CREA during the European project Europruning).
[f] [14].
[g] [27].

Fig. 2. Innovative pruning chipper developed by ONG (mod. PC50) during the European project Europruning [23].

machine. Therefore, the balers should be seen as a component (the main component) of a collection system irrespectively the type of bale. Nevertheless, information on the bale size is reported in Table 4.

Today, pruning balers are mainly used for vineyard pruning [12,41,42], because the small diameter of the shoots is easier to bale. In fact, baling long, thick branches can be difficult and represent the real limit for this technology which, according to our experience, works better with thin branches like vine or kiwi shoots.

However, the harvesting of other orchard plantations has been documented [2,11,43e45]. Baler is towed by a tractor and supplied with power from the PTO.

The main configurations of the balers are (Tables 1 and 4):

Windrowing plus harvest with standard hay baler (BL1). Standard hay baler with a modular header or a standard hay pick-up. This system enables thicker branches to be baled. Only one model is currently available.

Table 4
Technical and productive features of the main balers.

Company	Model	Configuration (Table 1)	Working width (mm)	Weight (kg)	Bale characteristics mm (kg)	Min. Power (kW)	Productivity t h^{1} (ha h^{1})	Specie harvested
Anderson	Biobaler WB66	BL2	2250	6820	1200 Ø 1200 ()	150	8e20[a] 0.38 (0.85)[b]	e
Caeb	Quickpower 730CNG	BL4	1200	1000	400 Ø 450 (16.3)	14 at PTO		Vitis vinifera, L.
Caeb	MP 400	BL2	750	550	600 Ø 400 ()	15 at PTO	1.8 (0.17)[c]	Actinidia chinensis, P.
Caeb	MP 400/S	BL2	750	498	600 Ø 400 (31)	15 at PTO	1.68 (0.74)[d]	Vitis vinifera, L.
					600 Ø 400 (15)		0.5e1.2[e]	Corylus avellana, L.
Caeb	Quickpower 1230	BL2	1310	550	600 Ø 400 ()	15 at PTO	0.5[e]	Corylus avellana, L.
Lely	Welger RP320	BL2	2250	3260	1250 Ø1500 ()	33	2.4 (0.5)[e] 2.3 (0.19)[f]	Prunus persica, L. Olea europea, L.
Lerda	T110	BL1	1190	1360	1100 Ø 1000 ()	26e34	0.31e0.43 (0.61 e0.64)[g]	Vitis vinifera, L.
Lerda	T135	BL2	1500e1850	1950	1350 Ø1220 (484 e493)	65e55	2.90[e] ()	Corylus avellana, L.
Lerda	900L	BL2	750	900	400 300 x 600 (31)	40	1.15[d] ()	Vitis vinifera, L.
Lerda	1100L	BL2	1200	1000	1200 350 x 450	15e20	1.30[e] ()	Corylus avellana, L.
PIMR	PRB 1.75 þ front mounted windrower	BL3	1850	2950 e3245	() 1200 Ø1200 (250)	40	3.03[h] () e	Malus domestica, L.
Serrat þ Claas	Class Quadrant 2100 Baler with Serrat T-2400 head	BL1	2000e2400	2000 e2200	800 Ø700 ()	51	(1e2)[i]	e
Tigieffe[f]	Arbor RS170	BL2	1300	760	1000 Ø500 ()	25	0.5 (0.42)[f] 0.7 (0.20)[f]	Prunus persica, L. Vitis vinifera, L.
Wolagri[j]	R98 Energy	BL2	1300e1900	1940	1200 980	38e50	e	e
	R12 Energy	BL2	1500e2100	2290	1550 Ø1200 ()		e	e

a Website of the machine manufacturer [69].
b [12].
c [5].
d [8].
e [65].
f [44].
g [42].
h [1].
i Website of the Gobierno de Espana. Ministerio de Agricultura y Pesca, Alimentacion y Medio Ambiente [70].
j Website of the machine manufacturer [71].

Windrowing plus harvest with rear baler (BL2). Few models. The level of adaptation for pruning collection, the quality and compactness of bales depend on the brand.

Integrated windrowing and harvest with rear baler (BL3). Only one model has been reported in Europe, developed as part of the Europruning project [1]. Able to windrow and bale pruning in one pass. Windrower can also be placed at the front of the tractor.

Windrowing plus harvest with front-mini-baler (BL4). Produced by an Italian company, and suitable for vineyards with narrow planting layout [12].

The size of the bales can vary, as can their mass (Table 4).

As previously mentioned, balers are essentially an adaptation of conventional straw balers, or are designed specifically for baling pruning residue, which lack the necessary uniform shape. The size (height and width) is an important requirement for the machines to be able to move along different crop layouts. Various commercial mini roto-balers for harvest pruning are available on the market. These have the same function as the standard forage balers but produce smaller bales (30 kg bales) and the characteristics of the branches to bale has to be controlled (thickness and length).

Some balers producing round bales of standard dimensions (1200 mm 1200 mm) have become available but could be improved by including a crushing system in the pick-up before going into the round baler chamber. A machine was developed by the Anderson Group as model WB-55 [46,47]. The system was tested on willow [46] and eucalyptus [48] with an average harvest productivity of 7.7 (willow) or 8.9 (eucalyptus) t h^1. The machine cuts standing stems, partially shreds the cut stems providing a sort of a coarse mastication rather than a fine comminution [48]. A mulcher roll produces uneven-size fragments that facilitates baling and reduces the risk of microbial attack. However, it was conceived for harvesting SRC energy crops and forestry residues and no data are available on harvest pruning.

Large-sized bales are efficient in terms of pruning collection, but create more problems since comminution is required before use these at the plant [7,45]. An alternative has been proposed in Ref. [42] using a mixer wagon, commonly used for cattle feeding with a comparable cost to a small-medium chipper. However, the preferential use on vineyard plantations posed some problems related to the length of the pruning, the width of the rows and the slope of the terrain [42]. tried to find the best compromise between the machine width and bale size by replacing the tires with iron rollers. Other implements have been developed for constrained spaces and/or steep terrain such as hillside vineyards and mountain viticulture. The a mini-baler system has been proposed as a possible solution [12]. However, it was more expensive than full-size tractor-powered residue harvesters, but lower than the cost for field burning or pruning disposal [12]. Thus, Spinelli et al. [12] proposed concentrating pruning residues in alternate rows, to double the field stocking. Although, this recommendation specifically referred to mountain vineyards [12], the concept could be extended to all pruning and considered as a general rule in pruning collection.

Experiences in olive and peach pruning in some cases confirmed the problems related to the movement of machines in narrow spaces [11], also highlighting new issues regarding the variability of biomass in terms of length, diameter and flexibility of pruning.

During the Europruning project, an innovative system to windrow, collect and compact branches from pruning was developed by PIMR (Fig. 3). The baler (mod. PRB 1.75) [1], trailed by the tractor (minimum power of 40 kW), was designed to rake and press into bales different size prunings and produced on different soil conditions. It includes a pick-up system in which the height is controlled by a wheel or anti-sinking skids. Material is picked up by an over-ground rotating raking device, using tines in stony soils.

For the balers, the maneuverability of the machine in fields with different plant distances, the harvesting speed, the loss of products are challenging for manufacturers and researchers. Bale collection has some advantages especially when prolonged storage and a higher biomass health are required. However, the entire chain (including logistics, transport and comminution at the plant) needs to be further optimized through the effective organization of bale collection.

3.6. **Pre-pruners integrated with harvesting**

Pruning is an obligatory operation usually carried out manually, and aimed at improving the fruits' yield and quality. Mechanical pruning has been phased out, in order to integrate the tree architecture and the type of mechanization [49e51]. However, it has only been extended to vineyards [52,53], even if it is becoming common also in other plantations.

Multiple machinery builders have mechanical pre-pruners which could be adapted for an integrated collection of biomass. This is not necessarily a complicated issue, but more a question of conveying the pre-pruned branches effectively to a container (Table 1):

Pre-pruning integrated with collection and shredding/chipping (PP1). Although such a solution does not for the moment exist in Europe, this is more straight forward than the automotive option.

Pre-pruning integrated with collection and shredding/chipping in an automotive machine (PP2). The machinery cuts the branches and conveys them to a shredder. From there, a fan blows the pieces into a bin. The solution is also equivalent to an automotive system conveying the pieces to a trailer.

Only one practical commercial solution exists which performs both pruning and pruning residue recovery in olive groves [35]. The machine integrates a pruning system (a lateral multiple-disc cutting bar) with some elements more typical of a shredder, such as a collection tube, a swinging-hammer grinder, and a dischargeable rear bin. Tested in an olive grove, a material capacity has been reported of between 0.33 and 1.03 $t_{f.b.}$ H^1 [35]. The machine is of interest for future developments mainly in olive groves where fully-mechanized pruning is carried out.

3.7. Stationary chipping of the pruning stored at the side of fields

Chippers or shredders can be mounted on a truck fed by a mechanical crane or manually by operators, and work in a fixed position at the border of a field after the pruning has been collected together by a tractor with fork. Many firms produce stationary chippers and various types of machines are available on the market. The majority of these have been developed for forestry use. This type of equipment and pruning management are not analysed in this survey which focuses on mobile pruning harvesters.

However, according to the evaluation of systems for harvesting biomass residues carried out by Velazquez-Martí et al. [54], this method was more efficient than mobile chippers, which are driven inside the orchard. Even though, it must be to highlight that the pruning handling with tractor equipped with fork could dramatically increase the soil and stones incorporation in the wood residues that will be chipped afterwards (after drying), with all the problems this entails.

However, accumulating prunings and the subsequent comminuting should be considered as a good alternative to the mobile chippers or shredders when a new pruning supply chain is planned for development, and the space to store the pruning at the border of the fields is not a limiting factor.

4. A challenging choice

The machinery cited in the present review is already available on the market, however the business volume of pruning harvesters in Europe is a very small segment of the market for regular shredders, chippers and balers.

The types of plantation where the pruning can be collected are extremely varied. This has generated a corresponding creative effort to optimize the equipment and the combination of implements to produce a high grade fuel. For example, the pruning characteristics (quantity, length, and diameter) or the shape of the field can mean that the performance of the harvest varies a good deal in terms of time, fuel consumption and quality of product obtained. Many machines are shredders equipped with a medium/ small size hopper, or a big container. Some models have been developed to discharge the product into a big-bag hanging on the frame

Fig. 3. Innovative pruning baler developed by PIMR (mod. PRB 1,75) during the European project Europruning [23].

of the machine, or in a trailer that can be towed by a second rear tractor or beside the pruning harvesting machine. One implement performs the pruning and pruning collection in one step and is well suited to fully mechanized orchards. Some equipment has been developed for the forestry sector to process prunings with a large diameter.

Of the types of pruning, vineyard pruning residues are the most common, however most vineyards offer difficult harvesting conditions which means that conventional equipment cannot be used to collect the prunings. As a consequence, some manufacturers have developed machines that work in specific planting patterns, which are sometimes very narrow [12]. In general, the more integrated the machinery is, the more efficient the harvest, and thus, the higher the potential savings in terms of economics and GHG emissions during the harvest.

Thus, apart from the innovations in the pick-up, integrated windrowing, chipping system and built-in bins, other aspects should be taken into consideration when selecting a system of pruning collection. Some regard the technical issues of the built-in components, and incorporate advanced techniques and unique innovations, such as the size and position of wheels (side vs under body), maneuverability on slopes, height control, pick-up roller design, conveying system for the pruning, discharge system, overload protection, and clogging prevention.

On the other hand, there are other issues related the shape and type of field and type of pruning. These factors included the size for maneuvering between trees (width, height), length and maneuverability (for turning at the headland), type of pick-up (which influences the efficiency in pruning collection and maximum speed), the adaptability of the system to different sizes of branches, among others. In addition to issues related harvesting prunings and influence harvesting performance, the pruning stage itself represents the previous phase that is critical in starting an economically sustainable pruning supply chain for energy production. Some studies have observed an improvement in fruit quality, fruit production, and amount of woody biomass obtained by the combination of mechanical and manual pruning [54,55]. Thus, equipment such as “Speedy-cut”, a self-propelled machine that provides one pass pruning and harvest pruning [35], may further improve the cost effectiveness and efficiency of the pruning supply chain.

Where only manual pruning is applicable, pruning alignment (accumulation of the prunings in windrows) represents a cropping practice that is crucial to improving the performance of the pruning harvesting phase and consequently to reducing the harvesting costs. In fact, accumulating pruning residues in windrows increases the field stocking and consequently the field capacity of the harvesting machine chain, thus reducing the additional times required due to maneuvering the harvester in the field. Therefore, a better performance is possible where the prunings are accumulated in alternate rows [14].

In addition, where mechanical pruning is not applicable, accumulating the biomass directly in windows during the manual pruning stage would make the subsequent mechanical windrowing unnecessary with a consequent reduction in the supply chain costs and the residue losses. Again, the manual alignment of the pruning would also improve the quality of the final comminuted product. In fact, when the prunings are pulled in swaths by mechanical windrowers (e.g. rotary rakes), the increased dust (soil particles) created during the process could contaminate the pruning more than with manual alignment with a consequent increase of the ash content in the final product.

5. **Future perspectives**

Innovations in pruning harvesters should mainly focus on improving machine performance and wood-fuel quality. Prunings harvested by shredding produce a low quality hog-fuel which can create problems during the biomass storage (high dry matter losses, low energy content, environmental emissions) with consequent problems during the thermochemical conversion, and possible clogging during the feeding to the boiler. Thus, designing machines that produce high-grade woodchips is key for the development of a sustainable and cost-effective supply chain for pruning. This can be achieved by introducing new cost-effective approaches such as:

- designing modular machines;
- using non-stop baling;
- increasing the energy content of the fuel.

Modular pruning harvesting machines should be adaptable for use in different field conditions and logistical situations. Modularity should be provided by both the cutting system and the temporary storage of the chips. The main features of the cutting system (type and number of cutting tools, speed of the rotors, rate of feeding) should be adjustable in relation to the pruning characteristics (length, thickness, age, amount, type of wood) so as to obtain a chip size distribution that complies with customer requirements. The same machine should also enable the most suitable system to be selected (big-bag) for storing the biomass during harvesting. Modular machines for harvest pruning do not currently exist, but are becoming proposed [56].

Baling has advantages over chipping in terms of storage. On the other hand, it requires additional steps before being used in power plants. For instance, baling performance is affected by the time required to unload the bale in the field. For forage and straw balers, new prototypes have been designed that provide a non-stop round baling. The first models are about to be marketed by companies such as Vermeer (https://www.vermeer.com), Lely (https://www.lely.com), Vicon (http://ien.vicon.eu) and Kverneland (http://ien. kvernelandgroup.com). It is likely that the same technology could be applied to pruning in the near future.

One of the weak points of the supply chain is the transportation of the biomass to the power plant. Wood biomass from short rotation forestry is transported by large trucks which require specific loading equipment and have a high rental cost [57,58]. Similar systems are used for pruning, as residues are also have a low energy content and decay rapidly. Thus in order to produce marketable wood-products, future pruning shredders should account for the densification of the woody material on-field during the harvesting. The direct production of agripellets or briquettes would increase the bulk density and the energy content of the fuel, thus reducing the transportation cost.

The first harvester combined with a pelletizer for the recovery of wheat residues was developed by Krone (Premos 5000). While performing the harvesting, the machine produces pellets (600e700 kg m^3) that work with wheat straw with a 13e18% of moisture content, which is crucial for pelletizing.

Nazzareno Costruzioni Srl has developed a stationary truck with an on-board pellet plant that produces agripellets (400e500 kg h^1) at the field edge starting from open-air dried pruning biomass [38,72]. As soon as the moisture content has decreased from 40-45% to 18e20%, the biomass can be pelletized directly on-field. The lack of an artificial drying process (which is common in the industrial production of wood pellets) has important consequences in view of the development of a sustainable agripellet supply chain [59]. In fact, it opens up the possibility of producing agripellets by pruning directly at the farm level, thus simplifying the logistics (no need for an external pelletizing machine), and reducing the production costs. This would shorten the supply chain of solid biofuel with a strong impact on product quality and the maximization of revenues. However, due to the high moisture content of the fresh pruning, harvesters combined with a pellettizer are not available on the market at present. In addition, initial results in prunings from vineyards and olive orchards have raised some reservations regarding the quality of the pellets [60e62]. Compared to the limit values of EN ISO 17225, pellets from vine shoots and olive branches might have a high ash content or low a lower heating value [63]. A viable path to exploiting pruning residues for pellet production could be to blend the residues with other wood biomasses in order to obtain an ideal pelletization [60,61].

An interesting solution for increasing the level of energy content transported with chips could derive from compactors. On poplar and locust wood chips [58], tested an Orkel MP2000 Compactor used for baling urban waste or for wrapping silage and milling products. The machine produced bales from piled woodchips. Interestingly, the processed material had a higher moisture content than required for pelletization (45e55%). However, as it was focused on the performance of the compactor, the work did not mention any decay problems. The system appears interesting for the logistics of agro-forestry residues such as the comminuted pruning, however the packing cost was still high.

6. Conclusions

The collection phase has a pivotal role in ensuring the profitability of pruning recovery and use. One specific type of machinery or solution does not exist, and currently-used machines do no match all types of field conditions. The choice of the best technology should be made on a case-by-case basis because the economic viability of recovering orchard prunings depends on how the costs of the residue are managed as well as on how the benefits are redistributed between orchard owners, harvesting contractors and biomass users.

However, harvesting is only one component upstream of the more complex chain of logistics, a process also involving transport, storage, handling and pretreatment. In logistics and supply chain management, optimization is a key issue, in order to reduce transport costs and lower carbon emissions generated by the machines. This entails analyzing factors such as the amount of pruning potentially available, the selection of the best harvesting method, the location of the energy plants, transport and pre-treatment, and a route optimization analysis. Traceability could also be added to this list, which is a key issue for the food sector, but still lacking in the biomass chain.

Although just one aspect of the overall process, harvesting prunings plays a pivotal role in building a sustainable and profitable collateral production and hence it needs to be define correctly. Various successful examples of well-designed pruning supply chains for energy production are already available in Italy. For instance, Fiusis s. r.l. (Calimera, LE, Apulia) use olive prunings produced by nine municipalities around the 1 MWe cogeneration plant which produces electricity (which is then sold on to the national grid) and heat. Fiusis's well-established harvesting solution entails the use of three Facma harvesters (Comby model) for use on farms that have up to 400 olive trees [64]. For farms with a higher number of olive trees, prunings are collected at the edges of the fields and chipped with a stationary shredder, a Caravaggi, with a production capacity of 10 t h^1 [64]. Chipping in both cases is carried out after a 25e30 day period in which the prunings are left in the field to ensure drying and leaf shedding [64].

Lungarotti Societa Agricola a. r.l (Torgiano, PG, Umbria) is another interesting and successful example of an Italian company that integrates wine production with energy production by vineyard pruning. This company uses roundbalers that produce 1.1 m wide and 1 m diameter bales of vineyard pruning. The bales are shredded by a mixer wagon, commonly used as animal feed, which has a comparable cost to a small-medium chipper but has the capacity to manage big bales like a more expensive large-sized woodchipper. The shredded biomass is burned and the steam produced is used for washing and sterilizing the bottling line, while the hot water is used to heat various areas of the winery (malolactic fermentation in barrique cellars, warehouse, offices). In this way the company is able to save 200 Mg per year of CO_2 and has reached almost 70% self-sufficiency in thermal energy [42,73].

This is an easily replicable process in other wine-growing companies. In fact, the potential availability of annual residues obtained from vineyard pruning is more than one Tg per year of dry matter. Approximately 200e500 kW electric power plants could be powered from the recovery of these residues giving an annual output of 0.8 TWh, which could meet the electrical requirements of 200 four-person families. Unfortunately, the excessive fragmentation of winegrowing companies makes this goal difficult to reach, but already recovering half of the pruning would be reduce emissions and increase farm income.

Note

Reference to specific makes and models is solely made for the purpose of helping readers correctly assess the study and does not involve any endorsement of specific makes and models to the exclusion of similar machines produced by other manufacturers.

Acknowledgements

This work was supported by the project SUSCACE (Supporto Scientifico alla Conversione Agricola alle Colture Energetiche e MIPAAF, D.M. 2419 of 20/02/2008) and the project EuroPruning (European Union - FP7/2007e2013, grant agreement no 312078).

References

[1] D. Garcìa-Galindo, E. Lopez, M.E.P. Gomez-Palmero, Europruning project: summary of final results, in: In Proceeding of 24th European Biomass Conference and Exhibition, June 2016, pp. 6e9. Amsterdam, The Netherlands, 6-9.

[2] D. Garcìa-Galindo, M.E.P. Gomez-Palmero, S. Germer, L. Pari, V. Alfano, et al., Agricultural pruning as biomass resource: generation, potentials and current fates. An approach to its state in Europe, in: Proceeding of 24th European Biomass Conference and Exhibition, June 2016, pp. 1579e1595. Amsterdam, The Netherlands, 6-9.

[3] S.B. Magar, P. Pelkonen, L. Tahvanainen, R. Toivonen, A. Toppinen, Growing trade of bioenergy in the EU: public acceptability, policy harmonization, European standards and certification needs, Biomass Bioenerg. 35 (8) (2011) 3318e3327.

[4] A. Messineo, R. Volpe, A. Marvuglia, Ligno-cellulosic biomass exploitation for power generation: a case study in Sicily, Energy 45 (1) (2012) 613e625.

[5] R. Spinelli, N. Magagnotti, C. Nati, L. Pari, J. Vanneste, Recovering kiwifruit pruning residues for biomass production, Trans. ASABE 55 (1) (2012) 21e28.

[6] A. Dyjakon, J. den Boer, P. Bukowski, Europruningea new direction for energy production from biomass, Agr. Eng. 18 (2014).

[7] L. Romanski, A. Dyjakon, F. Adamczyk, P. Fra¸ckowiak, Problems with deriving the fruit tree pruned biomass for energy use, Agr. Eng. 18 (2014).

[8] R. Spinelli, N. Magagnotti, C. Nati, Harvesting vineyard pruning residues for energy use, Biosyst. Eng. 105 (3) (2010) 316e322.

[9] N. Magagnotti, L. Pari, G. Picchi, R. Spinelli, Technology alternatives for tapping the pruning residue resource, Bioresour. Technol. 128 (2013) 697e702.

[10] L. Pari, S. Croce, A. Acampora, A. Assirelli, Prove comparative di soluzioni commerciali per la raccolta delle potature di olivo, in: L. Pari (Ed.), Lo Sviluppo Delle Colture Energetiche in Italia. Il Contributo Dei Progetti Di Ricerca Suscace E Faesi, Nuova Cultura, Roma, 2011, pp. 885e895.

[11] L. Pari, F. Sissot, Prove di raccolta di cascami di vite e pesco con imballatrice Arbor RS 170, L'Informatore Agrar. (12) (2001) 87e91.

[12] R. Spinelli, C. Lombardini, L. Pari, L. Sadauskiene, An alternative to field burning of pruning residues in mountain vineyards, Ecol. Eng. 70 (2014) 212e216.

[13] R. Spinelli, C. Nati, L. Pari, E. Mescalchin, N. Magagnotti, Production and quality of biomass fuels from mechanized collection and processing of vineyard pruning residues, Appl. energy 89 (1) (2012) 374e379.

[14] R. Spinelli, G. Picchi, Industrial harvesting of olive tree pruning residue for energy biomass, Bioresour. Technol. 101 (2) (2010) 730e735.

[15] A. Acampora, S. Croce, A. Assirelli, A. Del Giudice, R. Spinelli, et al., Product contamination and harvesting losses from mechanized recovery of olive tree pruning residues for energy use, Renew. energy 53 (2013) 350e353.

[16] A. Monti, N. Di Virgilio, G. Venturi, Mineral composition and ash content of six major energy crops, Biomass Bioenergy 32 (3) (2008) 216e223.

[17] R. Spinelli, E. Cavallo, L. Eliasson, A. Facello, Comparing the efficiency of drum and disc chippers, Silva Fenn. 47 (2012) 1e11.

[18] V. Civitarese, A. Del Giudice, A. Suardi, E. Santangelo, L. Pari, Study on the effect of a new rotor designed for chipping short rotation woody crops, Croat. J. For. Eng 36 (1) (2015) 101e108.

[19] A. Del Giudice, A. Assirelli, F. Gallucci, R. Bellacima, L. Pari, E. Santangelo, Production of energy feedstock from the riparian vegetation of Arundo donax (L.): suitability of the chopping systems, Ecol. Eng. 102 (2017) (2017) 459e467.

[20] M. Barontini, A. Scarfone, R. Spinelli, F. Gallucci, E. Santangelo, et al., Storage dynamics and fuel quality of poplar chips, Biomass Bioenerg. 62 (2014) 17e25.

[21] R. Spinelli, B.R. Hartsough, N. Magagnotti, Testing mobile chippers for chip size distribution, Int. J. For. Eng. 16 (2) (2005) 29e35.

[22] C. Nati, R. Spinelli, P. Fabbri, Wood chips size distribution in relation to blade wear and screen use, Biomass Bioenerg. 34 (5) (2010) 583e587.

[23] Europruning, Development and Implementation of a New, and Non Existent, Logistic Chain on Biomass from Pruning, 2013 e 2016. FP7-KBBE-2012. Ref number: 312078, http://www.europruning.eu/.

[24] uP_running, Take-off for Sustainable Supply of Woody Biomass from Agrarian Pruning and Plantation Removal, 2016-2019. H2020-LCE-2015. Ref number: 691748, http://www.up-running.eu/.

[25] AGROinLOG, Demonstration of Innovative Integrated Biomass Logistics Centres for the Agro-industry Sector in Europe, 2016-2020. H2020-RUR-2016. Ref number: 727961, http://www.agroinlog-h2020.eu/.

[26] SUGELLOG, Triggering the Creation of Biomass Logistic Centres by the Agroindustry, 2014-2017. IEE-ALTENER-2013. Ref number: IEE/13/638/SI2.675535, www.sucellog.eu/en/.

[27] A. Assirelli, S. Croce, A. Acampora, Potature di olivo da energia: le trincia caricatrici più adatte, L'informatore Agrar. 68 (25) (2012) 32e36.

[28] L. Recchia, M. Daou, M. Rimediotti, E. Cini, M. Vieri, New shredding machine for recycling pruning residuals, Biomass Bioenerg. 33 (1) (2009) 149e154.

[29] L. Pari, F. Sissot, Prove di trinciatura e raccolta dei cascami di potatura in campo, L'Informatore Agrar. (45) (2001) 1e5.

[30] C. Nati, N. Magagnotti, R. Spinelli, The improvement of hog fuel by removing fines, using a trommel screen, Biomass Bioenerg. 75 (2015) 155e160.

[31] R. Spinelli, L. Ivorra, N. Magagnotti, G. Picchi, Performance of a mobile mechanical screen to improve the commercial quality of wood chips for energy, Bioresour. Technol. 102 (15) (2011) 7366e7370.

[32] A. Assirelli, V. Civitarese, R. Fanigliulo, L. Pari, D. Pochi, et al., Effect of piece size and tree part on chipper performance, Biomass Bioenerg. 54 (2013) 77e82.

[33] R. Abdallah, S. Auchet, P.J. Meausoone, Experimental study about the effects of disc chipper settings on the distribution of wood chip size, Biomass Bioenerg. 35 (2) (2011) 843e852.

[34] M. Manzone, A bundler prototype for forestry and agricultural residue management for energy production, Int. J. For. Eng. 27 (2) (2016) 103e108.

[35] R. Spinelli, N. Magagnotti, C. Nati, C. Cantini, G. Sani, et al., Integrating olive grove maintenance and energy biomass recovery with a single-pass pruning and harvesting machine, Biomass Bioenerg. 35 (2) (2011) 808e813.

[36] L. Pari, A. Suardi, V. Alfano, A. Del Giudice, A. Scarfone, et al., Development of a new prototype of pruning harvester with helicoidal knife, 1-4, in: Proceeding of 23st European Biomass Conference and Exhibition, June 2015, pp. 47e48. Vienna, Austria.

[37] L. Pari, A. Suardi, A. Scarfone, A. Acampora, P. Frackowiak, et al., Harvesting of almond (Prunus dulcis, Mill.) pruning in Spain using a new chipper prototype, in: Proceeding of 24th European Biomass Conference and Exhibition, June 2016, pp. 6e9. Amsterdam, 6-9.

[38] L. Pari, V. Alfano, A. Scarfone, G. Toscano, Recupero di potature di vite per la produzione di agripellet. Valutazione di una trincia-caricatrice specificatamente progettata, Sherwood. For. Ed. alberi oggi 219 (2016) 14e18.

[39] CIRCE. reportEuropruning Project (KBBE.2012.1.2e01, Grent Agreement: 312078). Deviverable Reporting 4.2. Recommendations on the Management of Large Storages of Piled Biomass. Report July 14th, 2016. Website: http://www.europruning.eu/web/lists/pubfiles.aspx?type¼pubdeliverables.

[40] G. Cavalaglio, S. Cotana, Recovery of vineyards pruning residues in an agroenergetic chain, Peach 2 (2007) 0e2.

[41] C. Bisaglia, M. Cutini, E. Romano, Esame di una filiera per il recupero energetico da residui di potatura in vigneto, in: In Proceeding of Atti del Convegno Nazionale di medio termine dell'AIIA "Gestione e controllo dei sistemi agrari e forestali", Belgirate (VB), 2011, p. 6, 22-24 settembre.

[42] G. Cavalaglio, S. Cotana, Recovery of vineyard pruning residues in an agroenergetic chain, in: Proceeding of the 15th European Biomass Conference & Exhibition, 2007, pp. 1631e1636.

[43] P. D'Antonio, C. D'Antonio, C. Evangelista, V. Doddato, Raccolta dei sarmenti di vite e olivo, Sherwood 183 (2012) 85e88.

[44] L. Pari, F. Sissot, Mechanised collection of agricolture pruning residues: work optimization, in: Proceeding of 1st World Conference on Biomass for Energy and Industry, June 2000, pp. 436e439. Sevilla, Spain, 5-9.

[45] L. Pari, F. Sissot, La rotoimballatura delle potature di pesco ed olivo, L'INFORMATORE Agrar. (42) (2001) 85e87.

[46] P. Savoie, P.L. Hebert, F.S. Robert, D. Sidders, Harvest of short-rotationwoody crops in plantations with a biobaler, Energy Power Eng. 5 (2013) 39e47.

[47] R. Spinelli, Supply of wood biomass for energy purpose: global trends and perspectives, in: Proceedings of the 22nd Annual Meeting of the Club of Bologna, 2011, pp. 13e14. November.

[48] S.P. Guerra, G. Oguri, M.S. Denadai, M.S. Esperancini, R. Spinelli, Preliminary trials of the BioBaler working in Brazilian eucalypt plantations, South For (2017) 1e5.

[49] A.B. Dias, J. Peça, A. Pinheiro, Long-term evaluation of the influence of mechanical pruning on olive growing, Agron. J. 104 (1) (2012) 22e25.

[50] M. Karkee, B. Adhikari, S. Amatya, Q. Zhang, Identification of pruning branches in tall spindle apple trees for automated pruning, Comput. Electron Agric. 103 (2014) 127e135.

[51] B. Martin-Gorriz, I.P. Castillo, A. Torregrosa, Effect of mechanical pruning on the yield and quality of 'Fortune'mandarins, Span. J. Agric. 12 (4) (2014) 952e959.

[52] C. Intrieri, I. Filippetti, G. Allegro, G. Valentini, C. Pastore, et al., The semiminimal-pruned hedge: a novel mechanized grapevine training system, J. Enol. Vitic. 62 (2011) 312e318, https://doi.org/10.5344/ajev.2011.10083.

[53] S. Poni, S. Tombesi, A. Palliotti, V. Ughini, M. Gatti, Mechanical winter pruning of grapevine: physiological bases and applications, Sci. Hortic. 204 (2016) 88e98.

[54] B. Velazquez-Martí, E. Fernandez-Gonzalez, A.J. Callejon-Ferre, J. EstornellCremades, Mechanized methods for harvesting residual biomass from Mediterranean fruit tree cultivations, Sci. Agr. 69 (3) (2012) 180e188.

[55] B.V. Martí, E.F. Gonzalez, The influence of mechanical pruning in cost reduction, production of fruit, and biomass waste in citrus orchards, Appl. Eng. Agric. 26 (4) (2010) 531e540.

[56] Pari L. Patent n. 001372039. Macchina agricola per la raccolta, cippatura, carico su carro oppure imballatura dei residui colturali arborei e/o erbacei. Issue date: 22/03/2010. http://www.uibm.gov.it/uibm/dati/Codice.aspx?load¼info_list_uno&id¼1418919&table¼Invention&#ancoraSearch.

[57] M. Manzone, P. Balsari, The energy consumption and economic costs of different vehicles used in transporting woodchips, Fuel 139 (2015) 511e515.

[58] M. Manzone, Efficiency of a compactor in wood chip volume reduction, Biomass Bioenerg. 80 (2015) 303e306.

[59] G. Toscano, Agripellet quale soluzione per il riutilizzo energetico dei sottoprodotti agricoli, in: Proceeding of Convegno. I sottoprodotti agroforestali e industriali a base rinnovabile. Normativa, recupero, conservazione, impiego, trasformazione e aspetti economici. La valorizzazione dei sottoprodotti nell'ambito agro-zootecnico, industriale ed energetico, Vol: 2, 26-27/09/2013, pp. 75e84. Ancona.

[60] M. Barbanera, E. Lascaro, V. Stanzione, A. Esposito, R. Altieri, M. Bufacchi, Characterization of pellets from mixing olive pomace and olive tree pruning, Renew. Energy 88 (2016) 185e191.

[61] A. Garcia-Maraver, M.L. Rodriguez, F. Serrano-Bernardo, L.F. Diaz, M. Zamorano, Factors affecting the quality of pellets made from residual biomass of olive trees, Fuel Process. Technol. 129 (2015) 1e7.

[62] M. Zanetti, B. Brandelet, D. Marini, A. Sgarbossa, C. Giorio, D. Badocco, R. Cavalli, Vineyard pruning residues pellets for use in domestic appliances: a quality assessment according to the EN ISO 17225, J. Agr. Eng. Res. 48 (2) (2017) 99e108.

[63] T. Miranda, I. Montero, F.J. Sepúlveda, J.I. Arranz, C.V. Rojas, S. Nogales, A review of pellets from different sources, Materials 8 (4) (2015) 1413e1427. [64] M. Piccinni, (owner of Fiusis s.r.l.). Personal Comunication. Demo-day Organized by CREA Institute during the Project AGROinLOG (EU Project Number 727961), Calimera (Italy). March 28th, 2017.

[65] C. Sonnati, V. Ughini, G. Malvicini GL,Facciotto, S. Bergante, Prime esperienze di potatura meccanica del nocciolo in Piemonte (Trials on hazelnut mechanical pruning in Piedmont), Corylus&Co. 1 (2012) 48e63.

Web references

[66] Costruzioni Nazareno Srl. Principio di Funzionamento Spezzettatrice ALBA per biomasse agricole. Website : http://www.nazzareno.it/it/prodotti/agripellet/ 000108.html (last access: 26/04/2017).

[67] Costruzioni Nazareno Srl. Principio di Funzionamento Spezzettatrice MAREV LUCE. Website : http://www.nazzareno.it/it/prodotti/agripellet/000044.html (last access: 26/04/2017).

[68] Peruzzo. Trinciatrice per sarmenti PERUZZO mod. COBRA COLLINA. Website : http://www.peruzzo.it/ita/110-trinciatrice-per-sarmenti-peruzzo-mod-cobracollina.html (last access: 26/04/2017).

[69] Anderson BIOBALER WB-55 Website : http://biobaler.com/wb-55.html (last access: 26/04/2017).

[70] Gobierno de Espana. Ministerio de Agricultura y Pesca, Alimentacion y Medio Ambiente. http://www.mapama.gob.es/ministerio/pages/Biblioteca/Revistas/pdf_Agrotec%2FAgrotec_2013_10_82_88.pdf. (last access: 26/04/2017).

[71] Wolagri COLUMBIA : R98 ENERGY. Web site: http://www.tonutti.it/products.php?cat¼14&prod_id¼42. (last access: 26/04/2017).

[72] Costruzioni Nazareno Srl. Impianti di produzione agripellet. Website : http://www.nazzareno.it/it/prodotti/agripellet/000017.html (last access: 14/08/ 2017).

[73] Lungarotti Societa Agricola a.r.l. Website: http://lungarotti.it/eng/ sustainability/(last access: 15/08/2017).

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Article

Pelleting Vineyard Pruning at Low Cost with a Mobile Technology

Giuseppe Toscano [1], Vincenzo Alfano [2,*], Antonio Scarfone [2] and Luigi Pari [2]

[1] Department of Agriculture, Università Politecnica delle Marche, 60131 Ancona, Italy; g.toscano@staff.univpm.it

[2] Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria (CREA), Centro di Ricerca Ingegneria e Trasformazioni agroalimentari, Via della Pascolare, 16, Monterotondo, 00015 Roma, Italia; antonio.scarfone@crea.gov.it (A.S.); luigi.pari@crea.gov.it (L.P.)

* Correspondence: vincenzo.alfano@crea.gov.it; Tel.: +39-06-906-753-15

Received: 7 August 2018; Accepted: 14 September 2018; Published: 18 September 2018

Abstract: The goal of this work was to test a patented pruning harvester and a mobile pelleting system specifically designed for the vineyard agripellet chain. Biomass was characterized before and after storage and after the pelleting stage. The performance, the fuel consumption, and the work quality of the harvester were assessed together with the productivity and the power consumption of the mobile pelleting system. Production costs of pellet were estimated for the whole logistic chain, considering two scenarios: Storage and pelleting directly at the farm site or at a dedicated location at variable distance from the fields. For comparison, the direct production of chips without pelleting was considered. Results indicate that harvester performance was quite good and comparable with commercial solutions; the chips produced exhibited excellent storage performance, allowing direct pelleting without forced drying; the pellet quality was good comparable with that produced from forestry biomass. From an economic point of view, in-field pelleting was the most cost-effective solution, with a good margin of profit up to 57€ t^{-1}; on the other hand, when transport to an intermediate storage center is necessary, profit margin reduces gradually and fades off at an average 50 km distance from the fields.

Keywords: agripellet; biomass; bioenergy; mobile pelleting plant; logistic chain; pruning harvester

1. Introduction

There is a growing interest in renewable energy sources because of the increasing price of fossil fuels and the related environmental concerns due to greenhouse gas emissions (GHG) [1]. Sustainable energy production can foster the neutral balance of GHG, especially when sources, such as lignocellulosic biomass, are highly available and their procurement does not interfere with food chains [2].

Bioenergy has a primary role in achieving the target set in the national Renewable Action Plans (nREAPs), accounting for almost 54.5% of the final energy consumption in Europe [3]. Solid biomass used for electricity, heating, and cooling production is the biggest source of renewable energy in the European Union (EU) and is considered key to achieving the 2020 renewable energy targets [4].

First generation biofuels, made from edible biomass (vegetable oils, cereals, beets, and sugar cane), raise several ethical and social issues. A solution that helps to avoid food/non-food competition is the use of lignocellulosic biomass, agroindustrial wastes, and agricultural residues [5].

Moreover, the sustainability of the production of biofuels and their availability became, in recent years, an object of debate and are still in the spotlight for the EU. Recently, the European Commission (EC) has revised the Renewable Energy Directive (RED), extending the sustainability criteria to solid and gaseous biomass fuels used for heat and power production [6]. The level of attention to sustainable production is also high because the demand for renewable energy is expected to increase remarkably in the next years. In fact, especially for biomass, scientists stress that traditional sources for bioenergy production would not be enough to meet future energy needs and to respond to the new targets of the EU 2030 framework for climate and energy policies [7,8]. This implies the need to find alternative and sustainable ways to obtain lignocellulosic material to be exploited. In this regard, an interesting option is given by the agricultural residues or the byproducts and wastes from the agroforest and agroindustrial sectors [9].

Among the agricultural residues, pruning is considered an important biomass resource, because of its large availability in Europe [10]. In Italy, a large quantity of pruning derives from vineyards, a source of biomass that has already attracted the interest of scientists for both availability aspects and fuel characteristics [11]. Vineyards are grown over 3.2 million ha in Europe [12], of which 725,000 ha are in Italy, according to national statistics [13], resulting in high pruning biomass potential [14]. However, this biomass source is minimally exploited because of its low energy density and its poor suitability for direct utilization in small size plants. These limits in turn impede the growth of an optimized logistic chain focused on biomass pruning [10]. On the other hand, the densification process could represent a way to overcome these obstacles, furnishing high energy density products, which are easier to be managed and suitable for domestic heating systems. In 2013, Picchi et al. [11] showed that vineyard pruning is suitable for pellet production and for combustion in small-scale boilers. Moreover, the ISO 17225-1:2014 standard classifies vineyard pruning as woody biomass with code 1.1.7, namely “Segregated wood from gardens, parks, roadside maintenance, vineyards, fruit orchards, and driftwood from freshwater” and, according to ISO 17225-6:2014, such a biomass could be utilized to produce pellet defined as non-woody, which commonly takes the name of agripellet [15,16].

However, the harvesting and transport costs and the low quality of the material represent difficult obstacles to overcome [17]. The machines commonly used to collect pruning derive from conventional mulchers or shredders; these machines work fast, as they were conceived to clean up the fields rapidly and to limit fuel consumption; subsequently, the harvested products obtained have low quality characteristics in terms of storability, chip particle size, and inert contaminations. These are crucial characteristics in the post-harvest stages of the energy production chain [18]. To solve this problem, this work proposes an assessment of an innovative supply and production chain from harvest to pellet generation. The approach includes innovative machines and practical handholds for farmers, aimed at optimizing the quality of the product and the costs for production. The harvest was performed using a vineyard pruning harvester designed to preserve the quality of the fuel, while for densification a mobile milling-pelleting system was used to produce pellets directly at the farm site. This approach allowed the production of vineyard pruning chips that, after a period of open-air storage, were directly milled and pelletized in the storage site.

The goal of this work is to demonstrate the validity of the system through the evaluation of the performance of the machines and the quality of the agripellet produced together with an economic assessment of the production process.

The economic comparison with the commercial pellet is not finalized to compare a local versus an industrial chain, but to have reference parameters for quantifying the economic value of a new product. This was done to emphasize the economic sustainability of the short chain in the absence of the agripellet market, as shown by the results of the Pellets for Europe project developed in the Framework of the ALTENER Programme [19].

2. Materials and Methods

The work was divided into two phases, namely phase 1—pruning harvest and phase 2—pelleting. The activities were carried out between February and September 2016 around the municipalities of Illasi (Province of Verona) and Breda del Piave (Province of Treviso) in the Veneto Region (NE Italy).

2.1. Phase 1—Pruning Harvest

Pruning was harvested from a 30-year-old vineyard, variety Garganeca, located at Illasi, on a flat land, drip irrigated and with medium texture soil characteristics. The planting system was 4 m among rows and 0.8 m along the row, while the training system was a tendon.

Before the test, all plants were pruned manually, making sure to drop the cut part in the middle of the inter-row, forming an ordered windrow within each inter-row space. Then, the windrows were characterized, taking the mean width and height, respectively.

The machine used for the test is a patented pruning harvester, manufactured by Costruzioni Nazzareno, MAREV Alba 150 model, towed by a tractor Goldoni, model 70 Star with 50 kW power (Figure 1). The harvester has 1550 mm width, 3850 mm length, 1750 mm height, and a total weight of 2.8 tons. Frontally, the harvester has a pick up system formed by two overlapping rotors. The lower rotor has a length of 1500 mm, corresponding to the real working width of the machine. The rotor includes two converging augers, equipped with metal teeth, designed in a way to ensure the catchment, the conveying, and the lift of soil-free pruning from the ground. The upper rotor has a length of 1 m and is formed by ten lines of star-shaped disks. Each disk has eight tilted teeth, which push the biomass toward the chipping system. The chipping system is formed by a rotor equipped with special knives; it provides a net cut of the pruning and avoids the formation of shredded material. Details of chipping systems of different pruning harvesters, including the MAREV Alba 150 model, are furnished separately [20]. The presence of shredded fine particles in the stored wood chip piles tends to occlude the air spaces among chips, limiting air circulation and slowing down the dying process of the biomass. The persistence of moisture in wood chip worsens remarkably the storage performance of the biomass and promotes microbial degradation, as demonstrated by Pari et al. (2017) [21]. The chipped material is blown in a 3 m^3 bin (configuration for tendon trained vineyard) through a mechanic propulsion system similar to a tangential fan, formed by eight metal plates. The bin can reach 3 m height by means of a hydraulic pantograph in order to discharge the material. An 8 m^3 trailer was utilized to transport the chipped material to the storage site.

Figure 1. Pruning harvester manufactured by Costruzioni Nazzareno, MAREV Alba 150 model.

2.1.1. Evaluation of the Harvest Performance

The machine was tested on three replicated harvest test areas (blocks), created considering six pruning windrows for each block over a total surface of 0.74 ha. The performance was evaluated through the study of the working times according to the methodology adopted by the Commission Internationale de l'Organisation Scientifique du Travail en Agriculture (CIOSTA) and the Italian Society of Agricultural Engineering (AIIA) [22]. The main working times were: TO = total operating time, as sum of TE = effective operative time (% of operating time, TO), and TA = accessory time (% of operating time, TO).

Accessory time included the time for turning, refueling, unloading, and maintenance. Other working parameters were field efficiency (%), theoretical and effective speed (m s^{-1}), theoretical and effective field capacity (ha h^{-1}), working productivity (t h^{-1}).

The fuel consumption of the tractor was measured during the total operating work (including turning, unloading, rest, and machine regulations), through machine tank refilling until full level at the end of each block, using a graduated large cylinder.

Field biomass availability per hectare was calculated weighing the material obtained in each block (three replicates), using a tractor trailer and a certified weighbridge. Biomass losses due to the faults of the machine pick up were assessed by weighting the product left on the ground in six replicated plots of 10 m^2 randomly selected within the experimental field.

2.2. Phase 2—Pelleting

The test took place at the Costruzioni Nazzareno factory in Breda del Piave. The material was transferred to this location after an open-air storage period lasting eight months where it was harvested. Before pelleting, the moisture content was detected according to UNI EN 18134-1:2015 technical standard, in order to verify that the water content after storage was below 20% to allow such processing [23].

A mobile plant for pruning biomass densification, developed by Costruzioni Nazzareno, was utilized (Figure 2).

Figure 2. Mobile pelleting plant developed by Costruzioni Nazzareno.

The main elements of the system are the grinding mill, a 3 m^3 buffer tank for the accumulation of the milled material, and the pelleting system. The three elements are connected by means of pipes of suitable diameter through which the material is moved by a pneumatic system. All the elements are mounted on a trailer for road transport, in order to process the material directly on the field or at the dedicated farm structures. The loading of the biomass into the hopper is performed manually or mechanically. From here, a conveyor system transports the material to the refining mill that pulverizes the material until the particle size suitable for densification is obtained. An electric fan pushes the material inside the buffer tank, equipped with a filter to reduce dust emissions, where it is stirred by a flywheel. Successively, the material is transported to the press of the pelleting system. The pelletizer has a 6 mm diameter extruder, while the grinding mill has a grid of 1 mm. Both the grinding mill and the pelleting system are powered by a 35 kW electric engine.

2.2.1. Pelleting Performance

Productivity was assessed by weighing the pellet produced in one minute and repeating the measure 20 times randomly during the test. Moreover, the quantity of pellet produced in 20 consecutive minutes was weighed to validate the results.

In order to evaluate the power absorbed by the load, a current clamp was utilized to measure the line current.

Assuming a perfectly balanced three-phase power system (in a four-wire star-connected load), the total power is equal to three times the power absorbed by one phase, according to the equation:

$$P_t = 3 \cdot V_f \cdot I_f \cdot \cos\phi \quad (1)$$

where V_f and I_f are respectively the phase voltage and current, and $\cos\phi$ is the power factor.

For star-connected circuits:

$$V_l = \sqrt{3} \cdot V_f \text{ and } I_l = I_f$$

where V_l and I_l are respectively line voltage and current.

Considering the best power factor correction, $\cos\phi = 0.9$:

$$P_t = 3 \cdot \frac{V_l}{\sqrt{3}} \cdot I_l \cdot \cos\varphi = \sqrt{3} \cdot V_l \cdot I_l \cdot 0.9 \quad (2)$$

The current clamp display was recorded during the whole test. MPlayer software (1.3.0 version) a free and open media player, was used to automatically obtain a screen shot every 10 s, in order to read and average the measures.

2.3. Biomass Characterization

Biomass quality was assessed before the passage of the harvest machine (fresh pruning), after collection (fresh chips), after storage (dry chips), and after pelleting (pellet). In particular, five samples of fresh pruning and pellet were analyzed to determine the main fuel quality parameters, as summarized in Table 1. Fresh chips were exclusively characterized with respect to particle size distribution (before storage), moisture content, and bulk density (before and after storage). For moisture content and bulk density of chips, the same reference standard was used, as indicated in Table 1. On the other hand, for particle size analysis, five samples of 4-liter volume each were weighed and successively divided into four dimensional classes (<50 mm, among 50–100 mm, 100–120 mm, >120 mm). Then, the product of each dimensional class was weighed again for defining the percent incidence of each class on total sample weight. Meanwhile, a visual inspection of the material allowed the assessment of the quality of the cut and the cleanliness, by searching for foreign bodies such as soil or stones.

For the laboratory analysis, five samples of about 1500 g each of pruning and pellet were placed in non-breathable bags, sealed, and delivered to the Biomass Lab of Marche Polytechnic University. After the determination of parameters on fresh basis, the samples were oven dried at 105 ± 2 °C temperature until they reached constant weight, then milled with the Cutting Mill Retsch Sm 100, and finally sieved through a 1 mm mesh.

Table 1. Parameters analyzed on biomass according to the reference standards and technical procedures.

Parameter	Standard	Procedure
Moisture content	ISO 18134-1:2015	Samples were dried at 105 °C in forced ventilation oven.
Ash content	ISO 18122:2015	Samples were determined by a thermo-gravimetric analyzer (TGA leco Mod. 701).
Mechanical durability	UNI EN 15210-1	The sample was subjected to controlled shocks by collision of pellet against each other and against the wall of a rotating chamber.
Bulk density	UNI EN 15103	A standard container was filled with the portion of a given size and shape and weighted afterward.
Net calorific value	UNI EN 14918	An isoperibolic calorimeter (mod. C2000 basic, IKA) was used to determine gross calorific value. The net calorific value was determined starting from gross calorific value, water and hydrogen contents of the analytical sample.

Nitrogen	ISO 16948:2015	The determination was done by a Perkin Elmer CHN analyzer.
Sulphur and Chlorine	ISO 16994:2015	Sulphur and chlorine contents were measured by decomposition in calorimetric bomb with excess of oxygen and absorption of acid combustion gases in water. Detection of sulphate and chloride was performed by liquid ion chromatography (mod. 761 COMPACT IC; Metrohm).
Minor elements 1	ISO 16968:2015	The chemical analysis provided for the digestion of the biomass sample in a closed container, using a mixture of acids (HNO3/H2O2/HF) and microwave oven (mod. Multiwave 3000; Anton Paar, Graz, Austria). The mineralization product was then analyzed by inductively coupled plasma optical emission spectrometry (ICP-OES mod. Optima 2100; PerkinElmer).
Ash melting behaviour	UNI CEN/TS 15370	The determination was done by an ash fusibility analyzer (SYLAB—model IF 1600 F).

[1] Pb, Cr, Cu, Mn, Ni, As, Cd, Hg, Zn.

2.4. Economic Assessment

2.4.1. Economic Scenarios

Three scenarios were assessed (Table 2). Two possible pruning pellet production chains were identified, corresponding to Scenario (A): Storage and pelleting directly at the farm site, and Scenario (B): Storage and pelleting outside the farm in a centralized processing site. The first scenario is reliable in presence of large-scale farms with enough biomass and suitable infrastructures (storage yard, machineries for biomass handling, electric power availability). On the contrary, the second scenario occurs when intermediate storage is needed to gather pruning from several smaller farms in a centralized site. In this second scenario, aside from the pelleting cost, the goal of the study was to also determine the transport costs and the maximum distance at which biomass pelleting would be economically profitable.

Alternatively to pellet production, a third scenario with the utilization of pruning chips directly in a biomass plant (Scenario C) was considered; also in this case, the transport cost and threshold distance were assessed, as in Scenario B.

Summarizing, regarding the cost allocation, Scenario A includes the cost of harvest pruning and pelleting, Scenario B includes the cost of harvesting the pruning, transporting the chips, and pelleting, while Scenario C includes only the cost of harvesting the pruning and transporting the chips.

A reference market price of commercial pellets and chips was utilized to estimate the profitability of the three chains. According to the solid biofuels price list of the Chambers of Commerce of Milan referring to February 2015 [24], the reference price used for pellet was 210€ t^{-1} (for a purchase of a full cargo truck of A2 classified pellets in 15 kg bags, VAT excluded, without transport), while the reference price for chips was identified as 50€ t^{-1} (referred to biomass obtained from forest maintenance operation, for a purchase of a full cargo truck, VAT excluded, without transport).

Table 2. Economic scenarios: Two possible pruning pellet production chains and direct use of chips.

Scenario	Harvesting	In field Drying	Transport	Drying	Pelleting
A	Harvesting	In field drying	-	-	In field pelleting
B	Harvesting	-	Transport to intermediate storage and processing site	Drying	Pelleting at processing site
C	Harvesting	-	Transport to biomass plant for direct use	-	-

2.4.2. Cost Estimation

The estimation of the costs was conducted according to the methodology proposed by CRPA—Centro Ricerche Produzioni Animali in 2015 [25], with the assumptions showed in Table 3 (harvesting costs), Table 4 (transport costs), and Table 5 (pelleting costs). Concerning the harvesting and pelleting systems, ownership costs were calculated according to the data provided directly by the owners (purchasing cost, service life, resale), while operating costs were based on data directly measured during the field test: Fuel consumption (l h^{-1}), effective field capacity (ha h^{-1}), and material capacity (t h^{-1}) of the harvesting system, according to Section 2.1.1, and productivity and power consumptions of the pelleting system, according to Section 2.2.1.

The costs for drying were neglected because in all cases it was performed in open air without investing in any infrastructure or covering system.

Table 3. Harvesting cost data.

Parameter	Unit	Tractor	MAREV Alba 150
Power	kW	50	-
Investment	€	28,000	24,000
Service life	year	15	8
Resale	%	25	10
Interest rate	%	4	4
Insurance	%	0.25	0.25
Labor	€ h^{-1}	12	-
Fuel cost	€ L^{-1}	0.86	-
Fuel consumption	l h^{-1}	3.64	-
Repair factor	%	40	40
Maintenance factor	%	10	5

For the cost of transport, a medium power tractor (100 kW) and a 40 m^3 trailer, commonly used for agricultural practices, were considered (Table 4). The unitary cost (€ t^{-1} km^{-1}) was estimated by considering the hourly cost of the transport system, the bulk density of biomass measured in the field (Section 2.3), the load capacity of the trailer, and the travel speed of 40 km h^{-1}. The equation used is the following: [Hourly cost (€ h^{-1}) / Load capacity (t)] × [Distance (km) / Speed (km h^{-1})].

To determine the threshold distance for the transport of chips that would guarantee a profit margin, a calculation was done considering a depreciation of the A2 pellet price of 10%, due to the lower quality of biomass (189€ t^{-1} instead of 210€ t^{-1}), and a minimum profit margin of 30€ t^{-1} for the product sold. This conservative approach has been adopted to display with a good margin of safety the maximum distance of transport of chips without incurring in overestimations.

Table 4. Transport cost data.

Parameter	Unit	Tractor	Trailer
Power	kW	100	-
Load capacity	m^3	-	40.0
Investment	€	78,000	25,000
Service life	year	10	15
Resale	%	20	10
Annual usage	h	800	250
Interest rate	%	4	4
Insurance	%	0.25	0.25
Labor	€ h^{-1}	12	-
Fuel consumption	€ h^{-1}	14.0	
Repair factor	%	40	15
Maintenance factor	%	10	5

Table 5. Pelleting cost data.

Parameter	Unit	Mill	Pelletizer
Installed power	kW	35	35
Investment	€	10,000	60,000
Service life	year	8	15
Resale	%	20	10
Interest rate	%	4	4
Price of electricity	€ kW h^{-1}	0.17	0.17

Labor	€ h^{-1}	12	12
Repair factor	%	50	20
Maintenance factor	%	10	5

2.4.3. Annual Usage of Machineries

For a final definition of the cost, it was necessary to identify annual hours of usage; this parameter is dependent on different factors. In fact, a significant part of the cost is due to the amortization of the investment for the purchasing of the machines (24,000€ for the harvester and 70,000€ for the pelletizer), which are distributed over the potential machine service-life (respectively, 10 and 15 years). Indeed, the more hours the machine is used in its service-life, the lower the hourly cost will be. Among the factors affecting the annual hours of usage, the following were identified:

1. Biomass yield in the field (t ha^{-1});
2. Working productivity of the harvester machine, that is, harvestable tons of pruning per hour (t h^{-1});
3. Working productivity of the pelleting machine, that is, processable tons of pruning per hour (t h^{-1});
4. Harvest window due to agronomic and climatic factors.

Whereas the first three factors were measured, the fourth was estimated in a minimal and maximal hypothesis. The maximum hours of annual usage were estimated by considering the potential working days within a harvest window of 90 days, with an effective working time of 8 h per day. The window of 90 days corresponds to the maximum exploitable period in Italy to collect vineyard pruning, that is, between December (pruning period) and March (first spring tillage) [26]. Within this time interval, some days of inactivity were taken into account to exclude precipitations or unexpected inconveniences. The days of precipitation for the period of January–March were estimated using the regional data of the Regional Agency for Environmental Protection and Prevention (ARPA) of Veneto (http://www.arpa.veneto.it), which provides meteorological data for long historical series. From the database, a mean value of an historical series from 2014 to 2017 was utilized as reference data (38 days of precipitations for the period considered). An additional inactivity period of 2 days was considered to exclude time losses due to unexpected inconveniences (machine breakages, operator sickness, etc.).
Festivities were not taken into account, as the general habit of contractors in the harvest period is to rest during the raining days. Therefore, in the final estimation of the potential working hours within the 90 days of the harvest window, an effective working period of 50 days was considered as the most reliable for the use of one machine. The minimum hours of annual usage for the pruning harvester were set by considering a threshold below which the collection is no longer sustainable in economic terms, because the hourly harvesting cost would be higher with respect to the agricultural contractor price of 60€ h^{-1} for pruning shredding [27].

Regarding the pelleting machine, the annual utilization was estimated according to its working capacity (t h^{-1}), considering a working time of 8 h per day and the minimum and maximum pruning availability as provided by the harvest machine and supply basin.

3. Results

3.1. Harvester and Pelleting Performance

The total operating time (TO) was strongly affected by the time for unloading (39.8%), while no rests or delays occurred. The theoretical field speed was 1.31 m s^{-1} and consumptions were 4.23 L ha^{-1} (Tables 6 and 7).

Table 6. Working time of the harvester.

Parameter	Unit	Value
Effective operative time (TE)	%	45.55 ± 2.49
Turning time	%	14.67 ± 1.28
Unloading time	%	39.78 ± 1.87
Maintenance time	%	0
Total operating time (TO)	%	100

Table 7. Performance and fuel consumption of the harvester.

Parameter	Unit	Value
Field efficiency	%	45.55 ± 2.49
Theoretical field speed	$m\ s^{-1}$	1.31 ± 0.06
Effective field speed	$m\ s^{-1}$	0.60 ± 0.05
Theoretical field capacity	$ha\ h^{-1}$	1.88 ± 0.09
Effective field capacity	$ha\ h^{-1}$	0.86 ± 0.08
Working productivity	$t\ h^{-1}$ (f.b.) *	1.99 ± 0.18
Fuel consumption per tons of harvested pruning	$l\ t^{-1}$ (f.b.)	1.83 ± 0.06
Fuel consumption per area worked	$l\ ha^{-1}$	4.23 ± 0.15
Hourly consumption	$l\ h^{-1}$	3.64 ± 0.44

* f.b. = fresh basis.

The harvester worked on windrows 1.30 ± 0.16 m wide and 0.35 ± 0.01 m high. The amount of biomass collected by the machine was 2.31 ± 0.16 t ha^{-1}, while harvest losses were 0.39 ± 0.13 t ha^{-1}, corresponding to 14.2 ± 3.92 % of the total potential harvestable pruning.

The productivity of the pelleting system was 371.8 ± 27.4 kg h^{-1}. The mean electricity phase current was 111.3 ± 15.03 A, and the mean power absorbed by the load was 64.69 ± 8.74 kW.

3.2. Biomass Quality

After eight months of open-air storage, the moisture content of the chipped material decreased about 50%, passing from 39.9% to 19.0%. The bulk density showed a reduction from 151.3 to 112.9 kg m^{-3} (Table 8).

Table 8. Bulk density and moisture content of the chipped material before and after the storage.

Parameter	Unit	At harvest	Post Storage
Bulk density	(kg m^{-3})	151.3 ± 8.3	112.9 ± 7.4
Moisture content	(%)	39.9 ± 0.85	19.0 ± 0.72

As shown in Figure 3, 87% of the resulting chips were longer than 50 mm and distributed mainly in the class 50–100 mm (36%) and 100–120 mm (30%).

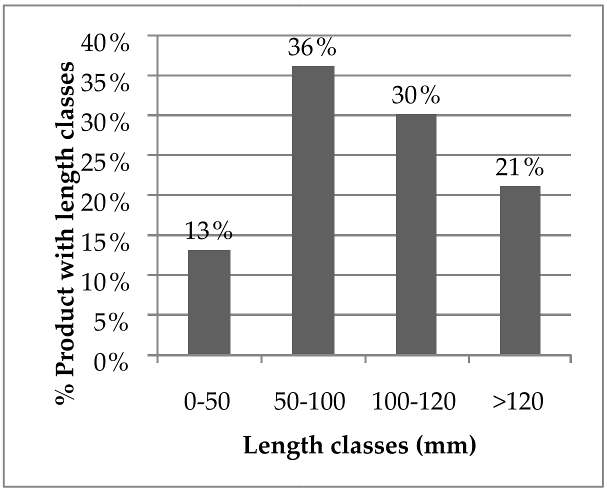

Figure 3. Particle size distribution of chipped material.

Table 9 shows the results obtained in the analysis of pruning and pellet; reference values of typical short rotation coppice pellets as provided by the ISO 17225-1 standard were also furnished. All parameters analyzed complied with the reference values, except for ash content and copper level.
Compared to fresh pruning, the ash content and the copper level of the pellet respectively increased by 0.3% (dry matter basis, dm) and 4.4 mg kg^{-1} dm. From an energetic point of view, pellets improved energy density, keeping a similar net calorific value, increasing bulk density about fivefold and reducing the moisture content of the chipped material threefold.

Table 9. Results of analysis for pellet and pruning with reference values typical for short rotation coppice pellet provided by the ISO 17225-1 standard.

Parameter	Unit	Pellet	Pruning	Typical Value of Short Rotation Coppice (1.1.1.3)—ISO 17225-1
Moisture content	w-%dm	6.9 ± 0.1	39.9 ± 0.8	Not defined
Ash content	w-%dm	4.2 ± 0.2	3.9 ± 0.3	0.5–4.0
Mechanical durability	% ar	98.3 ± 0.1	—	Not defined
Bulk density	kg m^{-3} ar	732.2 ± 9.3	—	Not defined
Net calorific value	MJ kg^{-1} dm	17.8 ± 0.1	18.0 ± 0.1	17.6–19.0
Nitrogen	w-%dm	0.59 ± 0.03	0.68 ± 0.5	0.2–1.4
Chlorine	w-%dm	0.05 ± 0.01	0.05 ± 0.01	0.01–0.18
Sulphur	w-%dm	0.03 ± 0.01	0.03 ± 0.01	0.01–.11
Arsenic	mg kg^{-1} dm	0.12 ± 0.01	0.18 ± 0.03	<0.4
Cadmium	mg kg^{-1} dm	0.15 ± 0.02	0.07 ± 0.01	0.2–5
Copper	mg kg^{-1} dm	17.2 ± 1.1	12.8 ± 2.5	2.0–4.0
Chromium	mg kg^{-1} dm	3.2 ± 0.5	2.3 ± 0.4	0.3–5
Mercury	mg kg^{-1} dm	<0.1	<0.1	<0.03
Lead	mg kg^{-1} dm	0.6 ± 0.1	0.5 ± 0.1	0.1–2
Nickel	mg kg^{-1} dm	0.9 ± 0.1	1.2 ± 0.1	0.2–3
Zinc	mg kg^{-1} dm	35 ± 6	27 ± 4	6–100
Deformation temperature	◦C	1376 ± 12	1392 ± 17	Not defined

ar: as received; dm: dry matter.

3.3. Economic Cost Analysis

In Scenario A (harvest + in-field drying and pelleting), according to possible supply basins, corresponding pruning availability and annual hours of machineries usage, the harvesting costs were assessed in a variable range from 16.2 to 30.5€ t^{-1}, while pelleting costs varied from 115.1 to 146.6€ t^{-1}, including ownership and operating costs. Therefore, harvesting affects from 12% to 17% of the total costs that varied from 131.3 to 177.1€ t^{-1} (Table 10).

Comparing these results with the reference market price of the commercial A2 pellet, depreciated 10% (189€ t^{-1}), the profit margin goes from 11.9 to 57.7€ t^{-1}. Therefore, for in-field pelleting, the minimum profit margin of 30€ t^{-1} will be achieved with a supply basin of about 150 ha. In this regard, as shown in Figure 4, the total cost and the profitability is directly related to the dimension of the supply basin.

The results obtained depend to a large extent on the price of fossil fuels. For instance, assuming a 50% increase in fossil fuel prices, the total cost for in-field pelleting increases by about 25€ per t, almost totally reducing profit margin (Table 11).

Table 10. Pruning harvesting and pelleting costs according to annual hours of machineries usage and supply basin needed (Scenario A).

Supply Basin (ha)	Pruning Availability(t)	Pruning Harvesting(h)	Harvesting Cost (€ h^{-1})	Harvesting Cost (€ t^{-1})	Pelleting (h)	Pelleting Cost (€ h^{-1})	Pelleting Cost (€ t^{-1})	Total Cost (€ t^{-1})
350	805	405	32.2	16.2	2165.3	42.8	115.1	131.3
300	690	347	34.2	17.2	1856.0	43.6	117.2	134.4
250	575	289	36.8	18.5	1546.7	44.7	120.2	138.7
200	460	231	40.8	20.5	1237.3	46.3	124.6	145.1
150	345	173	47.4	23.8	928.0	49.0	131.9	155.7
100	230	116	60.7	30.5	618.7	54.5	146.6	177.1

Table 11. Variation of the minimum and maximum agripellet chain cost (Scenario A), assuming a possible increase of fossil fuel price.

Cost of Agripellet Chain (€ t^{-1})	-	+10%	+20%	+30%	+40%	+50%
Min	131.3	131.5	134.7	142.9	148.7	155.8
Max	177.1	180.3	183.9	188.7	194.3	201.4

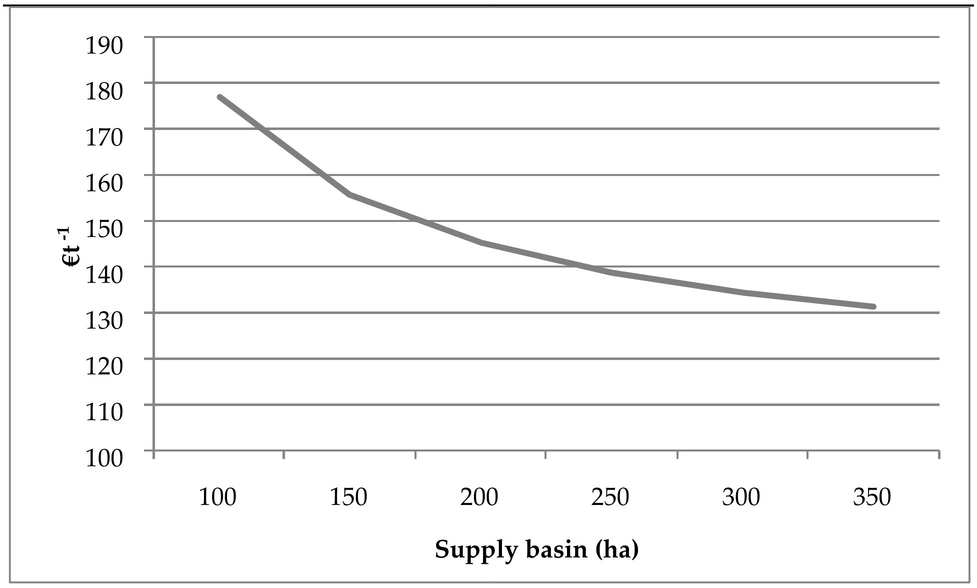

Figure 4. Total pellet production cost according to supply basin.

In Scenario B (pelleting in a centralized site), the transport costs were assessed in 0.53€ per km and ton of biomass transported, as shown in Figure 5.

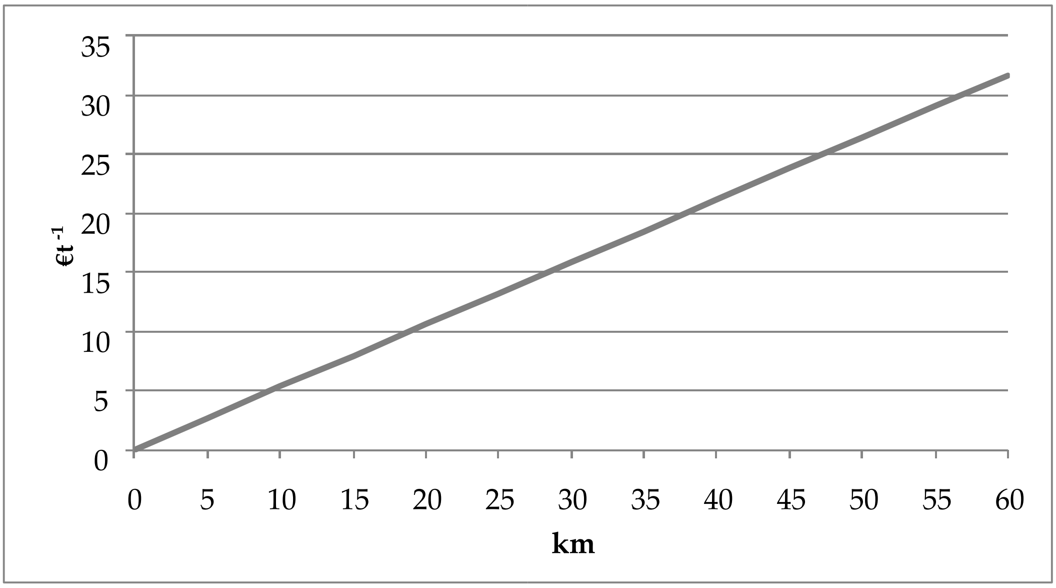

Figure 5. Transport cost (€ t^{-1}) according to the distance (km).

Hypothesizing a full exploitation of the harvest machine in the harvest window of three months (16.2€ t^{-1} cost for harvesting, 115.1€ t^{-1} for pelleting), the total cost, including the transport, reaches the threshold value of 159€ t^{-1} (ensuring a minimal profit margin of 30€ t^{-1}) at 52.4 km (Figure 6).

In Scenario C (direct use of the chips, without pelleting), considering a market price of the chips of 50€ t^{-1}, a profit margin above 30€ t^{-1} can be achieved only if transport is excluded (selling at the farm site) or if chips are transported within a distance of only 7.2 km (harvesting + transport cost is 20€ t^{-1}) (Figure 6).

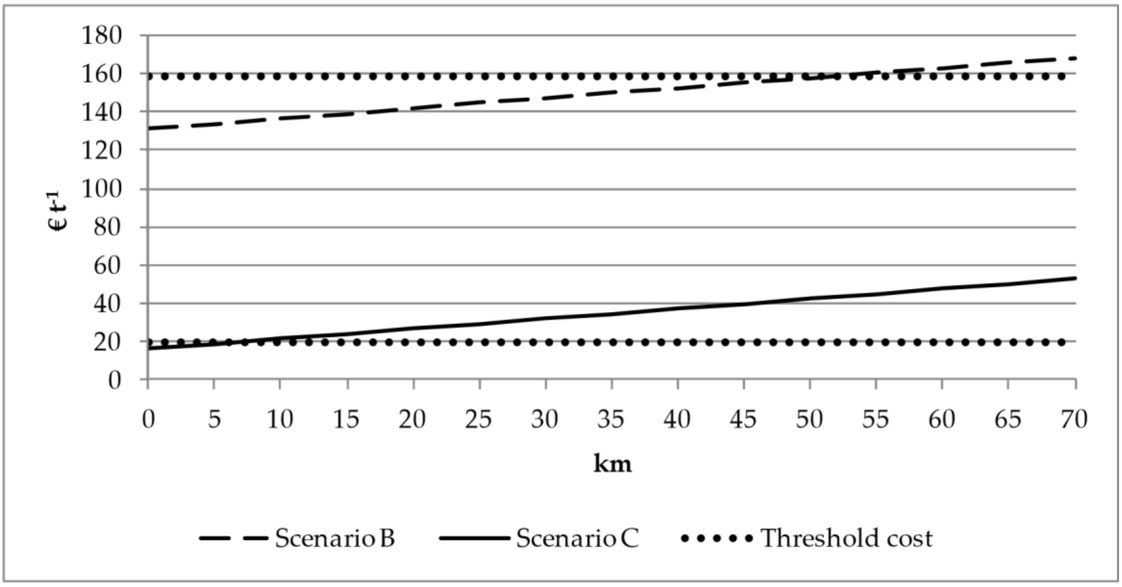

Figure 6. Trend of the production cost including transport in Scenario B (dashed line) and Scenario C (solid line). The crosses with the dotted line indicate the threshold distance of convenience, referring to a minimum profit margin of 30€ t^{-1}**.**

This calculation can change according to the expected profit margin and according to the dimension of the supply basin (availability of biomass). In fact, once a profit margin is fixed, the threshold distance in both Scenario B and C decreases with the reduction of the supply basin dimension. In the case of maximum exploitation, with a supply basin of 350 ha, the profit margin falls below 15€ t^{-1} at transport distance equal to 80.8 km (Scenario B) and 35.6 km (Scenario C) or becomes 0€ at 109 km (Scenario B) and 64 km (Scenario C) (Table 12).

Table 12. Threshold distance of convenience for Scenario A and Scenario B, according to supply basin dimension and expected profit margin.

Profit Margin (€ t^{-1})	Scenario/Threshold Distance (km)	Supply Basin (ha)					
		350	300	250	200	150	100
30.0	B C	52.4 7.20	46.6 5.30	38.5 2.84	26.4 np	6.3 np	np np
15	B C	80.8 35.6	75.0 33.7	67.0 31.3	54.8 27.5	34.7 21.2	np 8.52
0	B C	109.2 64.0	103.4 62.1	95.3 59.7	83.2 55.9	63.1 49.6	22.6 36.9

np: not profitable.

4. Discussion

The harvest machine was particularly efficient, generating chips with a particle size distribution 2/3 of which included chips between 50 mm and 120 mm, even suitable for feeding boilers without pelleting. The regular cut and the good particle size allowed high moisture losses to be reached in a short time during storage, rapidly reaching a value of moisture content which was lower than 20%, allowing direct pelleting and limiting dry matter losses due to microbial degradation. The harvester performance was comparable with other pruning harvesters for theoretical field capacity, but not for field efficiency [28,29]. The worst result was strongly affected by the high unloading time, because the machine filled up the small size bin very quickly.

This aspect could be improved by elongating the bin or changing the logistics, for example by working with two trailers at opposite sides of the field.

On the contrary, a lower fuel consumption than other commercial harvesters was achieved thanks to the possibility of using a low power tractor (50 kW).

Most chemical parameters analyzed in laboratory for pruning and pellet are comparable with the results found in previous studies [30–32]. The main variations refer to heavy metals, due to the different harvesting systems and storage conditions. In particular, the higher copper content is due to both pest-control chemicals applied to vines and to the soil picked up by the harvester. The latter aspect can also explain the higher value respect to raw pruning. Duca et al. [9] demonstrated, in fact, that much of the copper present in biomass is attributable to high presence in the soil. Concerning the moisture content reduction in the open-air pile, the regular cut of the chips and the particle size distribution contributed to the natural drying in by favoring air permeability, as also confirmed by previous studies [21,33].

Regarding the economic assessment, no previous studies were identified to deal with the topic of agripellet production with mobile technologies.

Several studies investigated the cost and marketability of the industrial production of agripellet, in particular from straw. In the Pellets for Europe project [19], the total cost for straw pellet was found to be in a range between 94 and 164€ t^{-1}; these results are lower compared to our findings, but they are based on industrial plants. Moreover, prices of straw refer to countries such as Denmark, which have small straw pellets markets.

Javier Sánchez et al. [34] calculated the costs for the whole pellet production chain for vineyard pruning. Only for pelleting, the average cost identified was 56.7€ t^{-1}, an amount lower than our estimations, but still referring to an industrial plant. On the other hand, pruning harvest costs were calculated as 19.7€ t^{-1}, confirming our findings, but lower than studies performed by Spinelli and Picchi [17], which estimated an average harvesting cost of 28 €t^{-1}.

The low costs of harvesting (from 12% to 17% of the total costs when storage and pelleting occur directly in the field) at first impact would suggest the convenience to include a second pruning harvester. On the other hand, at maximum exploitation, the use of two harvesters would require the use of two pelleting machines (540 working days), making the economic balance unsustainable. In fact, in the hypothesis of exploiting the harvest machine for the maximum time in the harvest window (405 h, i.e., 50 working days), the pelleting machine would work 2165 h per year (corresponding to 270 working days) to process the whole pruning collected; in this case, an area of about 350 ha would be needed and costs would be minimized at 131 € t^{-1} (Table 10).

As shown, the profitability of the agripellet chain is directly related to the dimension of the supply basin and, with this regard, the characteristics of the Italian farms limit the feasibility of Scenario A. In fact, vineyards are scattered in the national territory and the average size is only 1.96 ha [35]. This implies the need to bring the pruning from several neighboring farms in a centralized site where drying and the pelleting will occur (Scenario B). However, while profitability is guaranteed up to 50 km in the case of agripellet production, the direct use of the pruning chip (Scenario C), is cost-effective only when the biomass plant is very close to the fields. Nevertheless, the convenience for farmers is identified until a distance of 64 km, just for avoiding costs of field cleaning that are accounted for 60€ h^{-1} [27].

Basically, the agripellet chain from vineyard pruning in high productive wine areas like the Veneto region can provide a significant amount of additional green economy at local level. This would also reflect a positive social impact of the agripellet chain, which should be added to economic and environmental aspects. A more in-depth assessment should be performed in further studies, allowing for the measurement and comparison of the three dimensions of impacts, accounting for the interlinkages between the environment, economy, and society [36].

5. Conclusions

The study suggests that the harvester model MAREV Alba 150 can improve the perspective of using the vineyard pruning residues for the production of biofuels. In addition, vineyard chips exhibited good quality parameters, including ash content that was comparable with that of biomass obtained from short rotation forestry. These results are imputable to the pick-up system of the machine, which allowed collecting clean biomass, leaving in the field soil or other inert material.

The pellet generated presents good durability and high bulk density with an energy density of 13 GJ m^{-3}; these are both interesting characteristics for economic and sustainability aspects.

From an economic point of view, the main advantage of the mobile system is to cut down the transport costs of a low density biomass (chips). When pelleting takes place directly in the field, production costs are profitable, with a high economic margin compared to the market price of pellet. Profit margin gradually decreases when chips require to be transported outside the farm (Scenario B) and when the transport distance increases. In any case, the results obtained in this study open up interesting economic opportunities and suggest margins of profits which are higher compared to traditional wood-chip market chains.

Furthermore, the overall advantages of a local production chain, based on the sustainable valorization of residues (currently burned in the field), go beyond economic return. There are environmental and social aspects, not easily measurable, which are worth investigation in further studies.

Author Contributions: G.T. conceived and designed the research; V.A. and A.S. performed the research, analyzed the data, and wrote the paper; L.P. contributed materials/analysis tools.

Funding: This research was funded by the Project SUSCACE (SUpporto Scientifico alla Conversione Agricola alle Colture Energetiche), MIPAAF, D.M. 2419 of 20/02/2008.

Acknowledgments: This work was supported by the Project SUSCACE (SUpporto Scientifico alla Conversione Agricola alle Colture Energetiche), MIPAAF, D.M. 2419 of 20/02/2008.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Molino, A.; Larocca, V.; Chianese, S.; Musmarra, D. Biofuels production by biomass gasification: A review. *Energies* **2018**, *11*, 811. [CrossRef]
2. Arregi, A.; Amutio, M.; Lopez, G.; Bilbao, J.; Olazar, M. Evaluation of thermochemical routes for hydrogen production from biomass: A review. *Energy Convers. Manag.* **2018**, *165*, 696–719. [CrossRef]
3. Scarlat, N.; Dallemand, J.-F.; Monforti-Ferrario, F.; Banja, M.; Motola, V. Renewable energy policy framework and bioenergy contribution in the European Union—An overview from National Renewable Energy Action Plans and Progress Reports. *Renew. Sustain. Energy Rev.* **2015**, *51*, 969–985. [CrossRef]
4. European Commission State of Play on the Sustainability of Solid and Gaseous Biomass Used for Electricity, Heating and Cooling in the EU—Commission Staff Working Document. 2014. Available online: http:

//ec.europa.eu/transparency/regdoc/rep/10102/2014/EN/10102-2014-259-EN-F1-1.PDF (accessed on 6 August 2018).

5. Oh, Y.K.; Hwang, K.R.; Kim, C.; Kim, J.R.; Lee, J.S. Recent developments and key barriers to advanced biofuels: A short review. *Bioresour. Technol.* **2018**, *257*, 320–333. [CrossRef] [PubMed]
6. European Commission Proposal for a Directive of the European Parliament and of the Council on the Promotion of the Use of Energy from Renewable Sources. Available online: https://eur-lex.europa.eu/resource.html?uri=cellar:151772eb-b7e9-11e6-9e3c-01aa75ed71a1.0001.02/DOC_1&format=PDF (accessed on 6 August 2018).
7. European Parliament resolution of 5 February 2014 on a 2030 Framework for Climate and Energy Policies. A 2030 Framework for Climate and Energy Policies. 2014. Available online: http://www.europarl.europa.eu/sides/getDoc.do?pubRef=-//EP//NONSGML+TA+P7-TA-2014-0094+0+DOC+PDF+V0//EN (accessed on 6 August 2018).
8. Stelte, W.; Sanadi, A.R.; Shang, L.; Holm, J.K.; Ahrenfeldt, J.; Henriksen, U.B. Recent developments in biomass pelletization—A review. *BioResources* **2012**, *7*, 4451–4490.
9. Duca, D.; Toscano, G.; Pizzi, A.; Rossini, G.; Fabrizi, S.; Lucesoli, G.; Servili, A.; Mancini, V.; Romanazzi, G.; Mengarelli, C. Evaluation of the characteristics of vineyard pruning residues for energy applications: Effect of different copper-based treatments. *J. Agric. Eng.* **2016**, *47*, 22. [CrossRef]
10. García-Galindo, D.; López, E.; Gómez, M.; Sebastián, F.; Gebresenbet, G.; Jirjis, R.; Kern, J.; Germer, S.; Pari, L.; Suardi, A.; Dyjakon, A.; et al. Europruning Project: Summary of Final Results. Available online: http://www.etaflorence.it/proceedings/?detail=13021 (accessed on 20 July 2018).
11. Picchi, G.; Silvestri, S.; Cristoforetti, A. Vineyard residues as a fuel for domestic boilers in Trento Province (Italy): Comparison to wood chips and means of polluting emissions control. *Fuel* **2013**, *113*, 43–49. [CrossRef] 12. EC Eurostat Database. European Commission Online Statistical Database. 2017. Available online: https://ec.europa.eu/eurostat (accessed on 20 July 2018).
13. ISTAT Istat Database. Istituto Nazionale di Statistica Online Statistical Database. 2017. Available online: https://www.istat.it/it/agricoltura (accessed on 20 July 2018).
14. Motola, V.; Colonna, N.; Alfano, V.; Gaeta, M.; Sasso, S.; De Luca, V.; De Angelis, C.; Soda, A.; Braccio, G. Censimento Potenziale Energetico Biomasse, Metodo Indagine, Atlante Biomasse su WEB-GIS. Available online: http://editors.enea.it/it/Ricerca_sviluppo/documenti/ricerca-di-sistema-elettrico/ censimento-biomasse/rse167.pdf (accessed on 20 July 2018).
15. *ISO 17225-1:2014—Solid Biofuels—Fuel Specifications and Classes—Part 1: General Requirements*; International Organization for Standardization: Geneva, Switzerland, 2014.
16. *ISO 17225-6:2014—Solid Biofuels—Fuel Specifications and Classes—Part 6: Graded Non-Woody Pellets*; International Organization for Standardization: Geneva, Switzerland, 2014.
17. Spinelli, R.; Magagnotti, N.; Nati, C. Harvesting vineyard pruning residues for energy use. *Biosyst. Eng.* **2010**, *105*, 316–322. [CrossRef]
18. Zeng, T.; Weller, N.; Lenz, V. Mixbiopells: Enhancing the market relevance of alternative (mixed) biomass pellets in Europe. *19th Eur. Biomass Conf. Exhib.* **2011**, 306–314. [CrossRef]
19. Pellets in Southern Europe. The State of the Art of Pellets Utilisation in Southern Europe. New Perspectives of Pellets from Agri-Residues. Available online: https://www.researchgate.net/profile/Theocharis_Tsoutsos2/publication/263357353_PELLETS_IN_SOUTHERN_EUROPE_THE_STATE_OF_THE_ART_OF_PELLETS_UTILISATION_IN_SOUTHERN_EUROPE_NEW_PERSPECTIVES_OF_PELLETS_FROM_AGRI-RESIDUES/links/0c96053aa9da7f323b000000/PELLETS-IN-SOUTHERN-EUROPE-THE-STATEOF-THE-ART-OF-PELLETS-UTILISATION-IN-SOUTHERN-EUROPE-NEW-PERSPECTIVES-OFPELLETS-FROM-AGRI-RESIDUES.pdf (accessed on 6 August 2018).
20. Pari, L.; Suardi, A.; Santangelo, E.; García-Galindo, D.; Scarfone, A.; Alfano, V. Current and innovative technologies for pruning harvesting: A review. *Biomass Bioenergy* **2017**, *107*, 398–410. [CrossRef]
21. Pari, L.; Scarfone, A.; Santangelo, E.; Gallucci, F.; Spinelli, R.; Jirjis, R.; Del Giudice, A.; Barontini, M. Long term storage of poplar chips in Mediterranean environment. *Biomass Bioenergy* **2017**, *107*, 1–7. [CrossRef]
22. Bodria, L.; Pellizzi, G.; Piccarolo, P. *Meccanica Agraria vol II: La Meccanizzazione*; Il Sole 24 Ore Edagricole: Bologna, Italy, 2006; ISBN 8850651325.
23. Whittaker, C.; Shield, I. Factors affecting wood, energy grass and straw pellet durability—A review. *Renew. Sustain. Energy Rev.* **2017**, *71*, 1–11. [CrossRef]

24. Biomasse Legnose: Petrolio Verde per il Teleriscaldamento. Available online: http://www.fiper.it/uploads/media/invito-fiper-politecnico.pdf (accessed on 6 August 2018).
25. Costo di Esercizio Delle Macchine Agricole. Available online: http://www.informatoreagrario.it/ita/files/ 06-Costi-Mazzetto.pdf (accessed on 6 August 2018).
26. Veneto Agricoltura Gestione del Suolo. In *Guida per il Viticoltore*; Azienda Regionale Veneto Agricoltura: Legnaro, Italy, 2004; p. 94. Available online: http://www.venetoagricoltura.org/2007/01/editoria/guidaper-il-viticoltore-2004librocod-sc106esaurito/ (accessed on 6 August 2018).
27. Unione Nazionale Contoterzisti Agromeccanici e Industriali Tariffe per Lavori di Meccanizzazione Agricola 2015. Available online: http://www.contoterzisti.it/tariffe/TARIFFARIO%20UMBRIA.pdf (accessed on 6 August 2018).
28. Recchia, L.; Daou, M.; Rimediotti, M.; Cini, E.; Vieri, M. New shredding machine for recycling pruning residuals. *Biomass Bioenergy* **2009**, *33*, 149–154. [CrossRef]
29. Spinelli, R.; Nati, C.; Pari, L.; Mescalchin, E.; Magagnotti, N. Production and quality of biomass fuels from mechanized collection and processing of vineyard pruning residues. *Appl. Energy* **2012**, *89*, 374–379. [CrossRef]
30. Zanetti, M.; Brandelet, B.; Marini, D.; Sgarbossa, A.; Giorio, C.; Badocco, D.; Tapparo, A.; Grigolato, S.; Rogaume, C.; Rogaume, Y.; et al. Vineyard pruning residues pellets for use in domestic appliances: A quality assessment according to the EN ISO 17225. *J. Agric. Eng.* **2017**, *48*, 99. [CrossRef]
31. Picchi, G.; Lombardini, C.; Pari, L.; Spinelli, R. Physical and chemical characteristics of renewable fuel obtained from pruning residues. *J. Clean. Prod.* **2018**, *171*, 457–463. [CrossRef]
32. Manzone, M.; Paravidino, E.; Bonifacino, G.; Balsari, P. Biomass availability and quality produced by vineyard management during a period of 15 years. *Renew. Energy* **2016**, *99*, 465–471. [CrossRef]
33. Jirjis, R. Effects of particle size and pile height on storage and fuel quality of comminuted Salix viminalis. *Biomass Bioenergy* **2005**, *28*, 193–201. [CrossRef]
34. Javier, S.L.; de la Mora, C.F.M.D.; Marina, S.G.; Jesus, F.G. A proposal for pellet production from residual woody biomass in the island of Majorca (Spain). *AIMS Energy* **2015**, *3*, 480–504. [CrossRef]
35. Indagine Sulla Struttura e Produzioni Delle Aziende Agricole-2013. Available online: http://www.regione.lazio.it/binary/prtl_statistica/statistica_SPAA_argomenti/questionario_SPA_2013.pdf (accessed on 6 August 2018).
36. Van Schoubroeck, S.; Van Dael, M.; Van Passel, S.; Malina, R. A review of sustainability indicators for biobased chemicals. *Renew. Sustain. Energy Rev.* **2018**, *94*, 115–126. [CrossRef]

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Article

Testing Open-Air Storage of Stumps to Provide Clean Biomass for Energy Production

Luigi Pari, Antonio Scarfone *, Vincenzo Alfano, Simone Bergonzoli, Francesco Gallucci and Enrico Santangelo

Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA)—Centro di Ricerca Ingegneria e Trasformazioni Agroalimentari (CREA IT), 00015 Rome, Italy; luigi.pari@crea.gov.it (L.P.); vincenzo.alfano@crea.gov.it (V.A.); simone.bergonzoli@crea.gov.it (S.B.); francesco.gallucci@crea.gov.it (F.G.); enrico.santangelo@crea.gov.it (E.S.)

* Correspondence: antonio.scarfone@crea.gov.it; Tel.: +39-069-067-5254

Received: 15 September 2017; Accepted: 25 October 2017; Published: 27 October 2017

Abstract: When orchards reach the end of the productive cycle, the stumps removal becomes a mandatory operation to allow new soil preparation and to establish new cultivations. The exploitation of the removed stump biomass seems a valuable option, especially in the growing energy market of the biofuels; however, the scarce quality of the material obtained after the extraction compromises its marketability, making this product a costly waste to be disposed. In this regard, the identification of affordable strategies for the extraction and the cleaning of the material will be crucial in order to provide to plantation owners the chance to sell the biomass and offset the extraction costs. Mechanical extraction and cleaning technologies have been already tested on forest stumps, but these systems work on the singular piece and would be inefficient in the conditions of an intensive orchard,

where stumps are small and numerous. The objective of this study was to test the possibility to exploit a natural stumps cleaning system through open-air storage. The tested stumps were obtained from two different vineyards, extracted with an innovative stump puller specifically designed for continuous stump removal in intensively-planted orchards. The effects of weathering were evaluated to determine the fuel quality immediately after the extraction and after a storage period of six months with respect to moisture content, ash content, and heating value. Results indicated interesting storage performance, showing also different dynamics depending on the stumps utilized.

Keywords: stumps; bioenergy; storage; fuel quality; orchards

1. Introduction

The bio-economic framework of European Union opens up some interesting options to promote the valorisation of feedstock, until now considered as waste, such as forest and agricultural residues including chaff, straw, pruning, and stumps. Gonzalez-García et al. [1] demonstrated that the utilization of these residues for energy production is environmentally beneficial and has a lower impact than using wooden energy crops. Such biomass is generally left in the fields, but during the last decade there has been considerable research to find a way for its valorisation, receiving international funding and support [2].

Recently, the utilization of tree stumps as fuel is rising attention, as strategy to increase the forest potential to generate bioenergy. The stump is defined as the basal part of the tree, including the near-the-ground stem portion and the woody roots that remain after stem felling. Nowadays, stumps have gained interest as a biomass source for heat and power generation, due to the enlargement of the biofuel market and the decreasing prices for harvesting operations [3].

In some cases, the stump removal is considered a potential threat affecting soil fertility, biological sustainability, regeneration and survival of native species. It is the case of forests, where the stumps constitute a crucial habitat for many insect groups and other organisms or microorganisms that contribute to soil biodiversity [4]. In addition, soil damage due to compaction and removal of the essential nutrients present in stumps (e.g., N, P, K) can reduce the soil fertility [5]. Nevertheless, the results of these studies are often contradictory, as recent literature highlighted how the soil disturbance caused by stump extraction increased the mineralization of soil organic matter and the nutrient availability [6]. Other studies stress that stump harvesting creates better conditions for subsequent tree growth [7], producing a favourable environment for new orchard and forest plantations, as well as improving the quality and productivity of the site preparation and planting work [8]. However, going beyond this debate, there are certain conditions in which the removal of residual stumps is mandatory; it is the case of fruit orchards, in which the end-cycle plantations must be extracted or crushed for making space to new crops. Until now, common harvest techniques consist in the stumps removal with excavators, grinders, or extractors [9] equipped with a stump removal head, working on the removal of the singular root time y time. The excavator operator cuts the stump into smaller pieces to break off fine roots before extracting the stump and shaking it to remove excess soil. Stump pieces are then transported to a landing area using standard forwarders modified for stump haulage.

However, as several studies stressed the potential of forest-stumps from both natural forest and Short Rotation Forestry (SRF) to be used as fuel [10–16], a few of these works highlighted the opportunities and the impact that would be derived from the utilization of stumps deriving from orchards [17,18].

In case of intensive cultivations such as modern fruit orchards, these techniques become inefficient, as also demonstrated by Picchi et al. [17]. Therefore, the frequent turnover requires that termination costs are minimized to avoid overheads for the farms.

Another concern of stump harvesting is the massive soil disturbance, with consequences for soil organic matter (SOM) decomposition and emissions of CO_2 [19]. The stumps are normally extracted by excavators weighing 20–25 tons. To decrease extraction cost and time and reduce the soil damage, one possibility is to use light machines, towed by a tractor for single pass stump removal.

Recently, a mechanical stump eradicator manufactured by Officine Gottardo S.a.s and commercialized by La Cruz S.R.L. has been designed to solve the problem of end-life orchards removal in Italy. The machine (model SR100M) performs a continuous single-pass stump removal and represents the second version of a prototype already tested in Northern Italy on pear trees in 2012 [17]. In that experience, the machine showed higher field capacity and lower operating cost with respect a commercial excavator used for the same operation. However, the product quality was low, because both moisture content (MC) and soil contamination of the biomass were too high to allow commercialization and immediate conversion.

Indeed, the marketability of the stumps does not depend only from the extraction costs. In fact, the scarce quality of the fuel due to the high soil contamination may compromise any opportunity of commercialization. Therefore, parallel to affordable extraction systems, low-cost solutions should be identified in order to provide a marketable fuel.

In fact, if efficient recovery systems are identified, the growing biofuel market can provide an interesting opportunity to valorize this biomass resource, giving to farmers the chance to balance the cost for extraction.

In this regard, the identification of good storage techniques before energy conversion can play a significant role in improving biomass quality, as demonstrated by studies performed wih woodchips, forest residues, and whole plants. For instance, Barontini et al. [20] demonstrated that storing woodchips obtained from poplar tree crowns in open-air can improve the biomass quality and increase the energy yield of the product with respect the start condition. On the other hand, Lehtikangas and Jirjis [21] verified that the storage of logging residues can increase the wood fuel quality with respect to moisture content, heating value, and ash content. Walmsley and Godbold [22] stated that storage at the landing for up to a year allows rain and snowfall to wash off adhering soil and stones, which are fuel contaminants, and has the additional benefit of allowing the moisture content of the stump wood to decline substantially.

Hence, the authors claimed the need to identify cost-effective systems for biomass drying and cleaning before being processed into energy.

On the base of these findings, the objective of this work was to test the possibility to improve the biomass quality and the marketability of stumps of an end-cycle vineyard extracted with a specialized machine and stored in open-air piles for six months, i.e., exposed to meteorological agents.

The activity has been performed to test if the combination of such a storage system with the use of a specific machine for stump eradication would allow the farmers to increase payloads, and to obtain a product with a satisfactory quality for bio-energy production. The improvement of the biomass quality in a very affordable way would in turn determine the opportunity to exploit this still unexploited resource.

2. Materials and Methods

2.1. Test Fields

The study was conducted between February and August 2016 within the organic farm "Galileo Vini", placed in the Northern Italy at Vazzola ($45^{\circ}48^{0}23.43^{00}$ N and $12^{\circ}22^{0}03.99^{00}$ E), Treviso province. The area of the test was included in the alluvial plain of the Piave river as according to official soil map [23], at an approximate distance of 2.5 km from the main river bank. Climatic parameters such as precipitation, mean temperature, and mean daily solar radiation were recorded during the entire storage period using a whether cab certified by the Regional Environmental Protection Agency (n. 185, Tezze–Vazzola, Italy) and placed at an approximate distance of 2.0 km from the test fields.

The stumps were extracted from two distinct plantations in two rectangular flat fields, respectively 1.31 and 0.81 ha wide. In the larger field, the vineyard plantation dated 1989 and was a mixture of wine grape varieties including Chardonnay, Verduzzo, and Cabernet growth with a crop form called Bellussi. The layout was 8 × 4 m with plants grouped in the number of fours along the row (planting density of 1 plant each 8 m^2) and oriented in four opposite directions, forming a cross configuration. The second field hosted a plantation dating 1987, with a single variety (Cabernet), growth using the Geneva Double Curtain (GDC) system; the planting pattern of 4 × 1 m (planting density of 1 plant each 4 m^2) resulted in one stump each linear meter along the row.

Hand texturing revealed that both test fields presented a silt-loamy texture; the area was also characterized by the presence of medium size gravels that were removed prior to cultivation to allow mechanization. The soil moisture was determined in both fields at the moment of extraction, taking five samples from each field as according to the current standard methodology [24].

2.2. The Mechanical Extraction System

The extraction equipment was composed by a tractor Landini series 6–175 (166 Hp) and a single pass stump removal machine commercialized by La Cruz model SR100. The stump removal was composed by a iron frame, 3 cm thick, equipped frontally with two sub-soilers, 0.75 m long and spaced 1 m apart; the sub-soilers were connected at the base through a triangular horizontal blade.

Regarding functioning, during progress, the machine performs one horizontal cut with the basal blade and two vertical cuts with the sub-soilers; the working depth can be regulated by the hydraulic lift of the tractor as well as adjusted according to soil type, tractor power, and depth of the main root. As already observed in previous studies [17], this system in compact soils determine the formation of a soil block, including the root, which is separated from the rest of the ground. Successively, the plate is lifted up through four metal rods, 2.4 m long, hinged to the triangular basal blade and leant onto a rear rotor. The rods are inclined of about 30° respect the ground and space 23 cm from each other; this allow lifting of the sound block and the roots through a continuous sliding (Figure 1).

Figure 1. Machine La Cruz model SR 100 on work.

In loose soils, as the one of this study, the soil plate is not formed and stumps come out of the ground much cleaner. To remove the soil attached to the roots after the extraction, the machine shakes the material through a mechanism bouncing the rods up and down. In particular, the rear rotor of the machine presents pins welded in an alternative way, in correspondence of to the points where the rods are leaned on; when the rod is hit by the pin during the revolutions of the rotor, it is bounced up of about 20 cm and falls back for gravity to its foothold. Beside the pins, the rotor is equipped with curved metal teeth which allow further ground cleaning and facilitate the escape of the roots from the rear part of the machine.

Respect the previous version tested on pear orchards by Picchi et al. [18], the transmission of this machine is entirely mechanic. The power take-off (PTO) is connected to a mechanic reducer which transfers the power to two metal chins continuously thought two pinions. The lubrication of the chin is assured by a small independent hydraulic pump mounted on the top part of the machine frame.

2.3. Fuel Quality Parameters before Storage and Biomass Availability

After the extraction, 25 random stumps were taken from each field (50 stumps in total) to study the initial fuel quality parameters such as MC, ash content, heating value, and soil contamination level. To determine MC, 5 stumps of Bellussi and 5 of GDC were sampled as according to the methodology proposed by Laurila and Lauhanen [14]. Briefly, 500 g of wood in the midway between the main stump and the end of the root were cut using a chainsaw. The material was sealed in net bags and transported in the laboratory of CREA-IT (Monterotondo, Rome, Italy) together with the remaining 40 stumps to perform the analysis. In this regard, the analysis of MC was performed as according to the European standard valid for 2016 [25], which has been recently updated in the new one EN ISO 18134-2:2017 [26]. After the analysis, 50 g of minced samples were used for the determination of ash content and heating value as according to References [27,28], respectively, analyzing three replicates per each parameter.

To determine the amount of soil contamination at the extraction, 20 stumps of Bellussi and 20 of GDC were weighed in the field in correspondence of the extraction point; then, each stump was numbered and transported to another area for washing with high pressure cleaner. The stumps were then left in open-air for drying and reweighed after six hours to determine the amount of soil lost.

Biomass availability per hectare was evaluated, considering the weight of these 20 clean stumps per each field and multiplying the value for the number of stumpsha^{-1} as according to original plant density. The results are reported on dry basis.

2.4. The Storage Test

The biomass was then transported to a storage site close to the farm, consisting in a flat area of freshly mowed lawn. Two experimental piles were formed: one using 4.3 tons of Bellussi stumps and the other using 3.5 tons of GDC stumps. Each pile was about 5 m long, 5 m wide, and 3 m high. Despite the fact that the amount of biomass used in the Bellussi pile was 0.8 tons more, the different root morphology increased the volume of the pile, making the two piles of similar shape and dimensions. In this regard, GDC stumps were characterized by a high presence of secondary roots, having diameters lower than 2 cm, while in Bellussi the secondary roots were almost absent (Figure 2).

Figure 2. On the left a Geneva Double Curtain (GDC) root, on the right a Bellussi root.

Piles exposition was maintained as much similar as possible in order to guarantee the same surface exposed to weathering. The pile formation occurred manually soon after the extraction (T0) with the help of a farm vehicle (fork) that was used to arrange the material on the top of the stack (Figure 3).

Figure 3. Construction of vineyard rootstock piles: Bellussi right side, GDC left side.

After six months (T6, August), the piles were opened manually and 25 stumps per each stack were taken randomly for the determination of final fuel quality parameters—MC, ash content, and heating value. MC was determined using 5 of the 25 stumps from each pile following the procedure described for T0 [15]. The remaining 40 stumps (20 per pile) were brought at Centro di Ricerca Ingegneria e Trasformazioni Agroalimentari of Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria (CREA IT)for chipping and laboratory analysis. The chipper utilized was the Farmi Forest CX 260, while the laboratory instruments used were respectively the Memmert drying oven UN750 for MC, the Lenton laboratory Chamber Furnace EF 11/8B for ash, and the Parr 6400 Automatic Isoperibol Calorimeter for heating value.

The determination of the soil contamination after storage was carried by differentiating the piles in two layers (upper layer: 1.5 m < x < 3 m; lower layer: 0 m < x < 1.5 m) and analyzing the material of each layer separately. This was done to study the effects of open-air storage on cleaning performances in the two different pile's region, because it was expectable that soil would have accumulated largely in the lower layers of the stacks.

A number of 20 stumps were taken from each pile, respectively 10 from the upper layer and 10 from the lower layer (40 stumps taken in total), as shown in Figure 4. Each stump was weighted, cleaned with a high pressure cleaner, left to dry for six hours, and re-weighted in location close to the storage site.

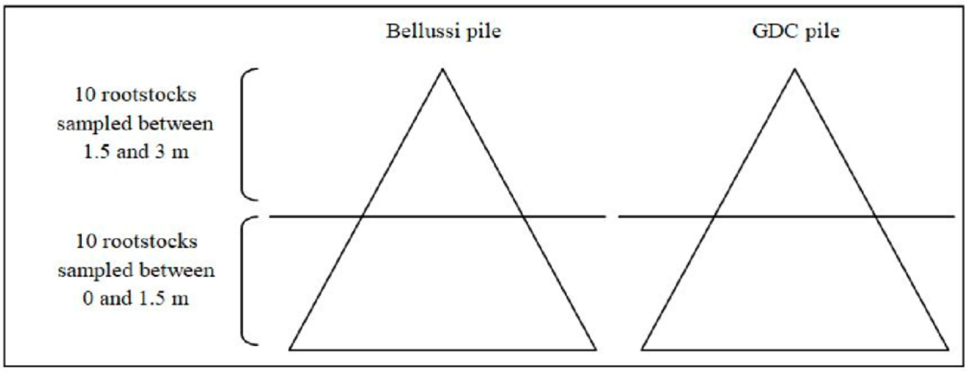

Figure 4. Scheme of the sampling methodology utilized to estimate the soil contamination after storage per pile's layers. Ten samples (replicates) were taken from both the upper (1.5 m < x < 3 m) and the lower parts (0 m < x < 1.5 m) of each pile and successively analyzed.

2.5. Statistical Analysis

Data were processed with PAST statistics software, version 3.15, to check the statistical significance of the difference between treatments. For the weather conditions, after checking the data for normality, a statistical analysis (Student's t-test) was performed, confronting the temperatures of 2016 with the mean of an historical series of six years (2010–2015) taken from ARPA Veneto (n. 185, Tezze–Vazzola, Italy). The Student's t-test was applied to the data of the stump's weight and MC as well. The one-way analysis of variance (one-way ANOVA) was applied to the percentage of soil contamination. In this case, the analysis was conducted after arcsine transformation, in order to satisfy the normality assumption.

3. Results and Discussions

3.1. Whether Conditions

During the six months of storage, the cumulative precipitations were 198 mm, with the biggest event recorded during the second week of February. Mean temperature as well as solar radiation were higher between the last two weeks of June and the third week of July (Figure 5), remaining for several days above 25 °C and 25 MJ·m^{-2} respectively.

Regarding temperatures, the comparison with the historical series reveled significant differences only for the months of February and June, which resulted significantly higher respect the mean at a level of significance of 5%.

An interesting consideration can be done regarding the frequency of rainy vs. sunny days. In fact, rainy days (daily precipitation above 1 mm) were in total 63, and an almost balanced alternation between sunny and rainy periods was noted. Only one big event was recorded in February, at the very beginning of storage. The fact that balanced and alternate periods of sun and rains would have influenced in a positive way the cleaning respect other conditions (e.g., only few concentrated rain events) was not demonstrated in this study, but it will be an aspect to be evaluated in future research activities.

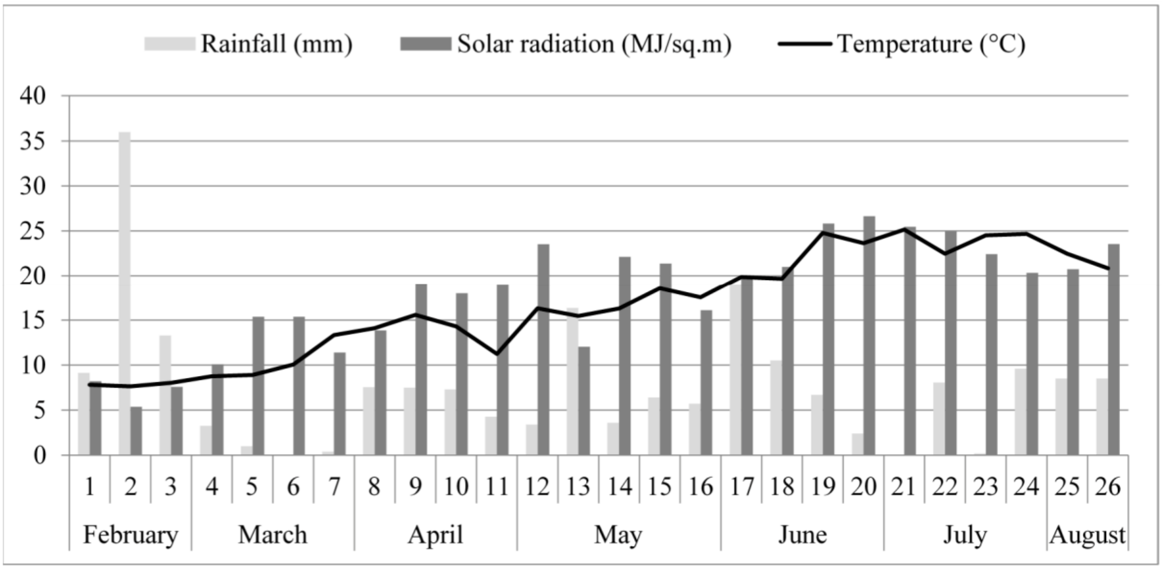

Figure 5. Climatic parameters recorded during the storage periods.

3.2. Fuel Quality and Biomass Availability

As not major differences were present among the ages of the plantations, morphological characteristics of the stump as shape and dimension were strongly affected by the plant form. The study of the 20 clean dry stump samples revealed that the unitary weight of Bellussi stumps was significantly higher than that of GDC stumps ($t = 3.72$, $p < 0.001$, $n = 20$). On average, the dry weight of Bellussi stump was 2.17 ± 0.68 kg, while that of a GDC stump was 1.38 ± 0.66 kg. Therefore, considering the original planting density of the two vineyards, the available dry biomass in Bellussi field was 2.71 ± 0.85 tons·ha^{-1}, while that available in GDC field was 3.45 ± 1.65 tons·ha^{-1}.

The MC of the biomass soon after extraction was in both Bellussi and GDC above 52%. From the beginning of storage (T0) to the end (T6), the MC decreased in Bellussi types until 12.4%, while in GDC until 11.5%. On average, the moisture lost was 40.3%, and no statistical differences were identified at T6 in the behavior displayed by the two stump types (Figure 6).

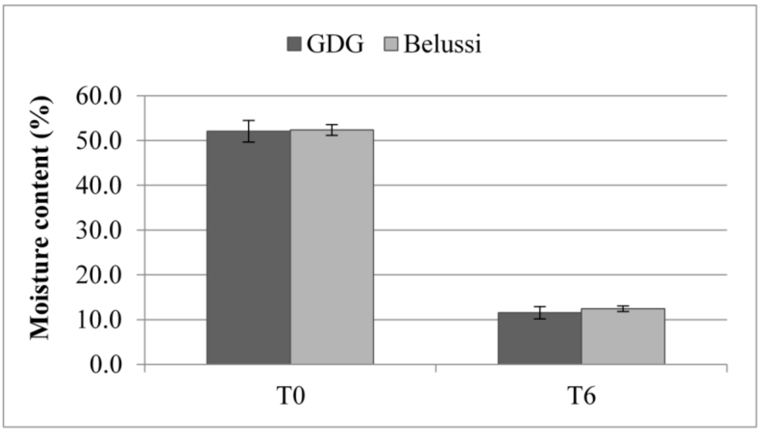

Figure 6. Mean (±SD) moisture content (MC) of the GDC and Bellussi stumps before and after the storage in piles.

If these results are compared with those obtained in other storage experiences with lingo-cellulosic material in similar environments [20,29], it is observable that the moisture lost by the stumps is much higher, demonstrating a greater attitude of the root material to lose moisture during open-air storage respect other woody parts. A number of studies on stump harvesting have been made in environmental conditions and wood species of North Europe [11,12,15,16]. However, although substantially different, the results of the present work must be compared with such observations. Different factors can affect the MC of the stump during storage. The main are the duration of the storage and the weather conditions, but the shape of the stump as well as the harvesting technique were proposed too. For instance, Anerud and Jirjis [9], deemed the duration as the main factor affecting the MC of Norway spruce stumps stored in a pile or in a windrow for 16 months. During this time, the MC decreases from 40–50% to around 20%, but the authors did not give any importance to the geographical location since the two sites had minimal differences in the prevailing weather conditions. Uri et al. [15] and Laurila and Lauhanen [14] agree about the role of storage duration. However, the second emphasizes also the role of temperature and air humidity in decreasing the MC. In our study, the storage duration was shorter than those of the above cited studies, but the Mediterranean climatic conditions played a pivotal role in decreasing the MC near 10%.

3.3. Soil Contamination before and after Storage

At the moment of extraction, the soil moisture was 17.7% on GDG and 19.6% on Bellussi fields. Statistical analysis performed through a T test revealed the absence of significant differences among the two fields ($p > 0.05$).

Immediately after extraction, the roots of Bellussi and GDC had respectively 6.62% and 8.86% of soil contamination; after six months, the stumps extracted from the Bellussi field showed a final soil contamination of 4.27% in the upper layer and 5.14% in the lower layer. The differences in the soil lost among the two layers were not significant. The pile of GDC showed a final soil contamination of 2.0% in the upper layer and 12% in the lower layer (Figure 7).

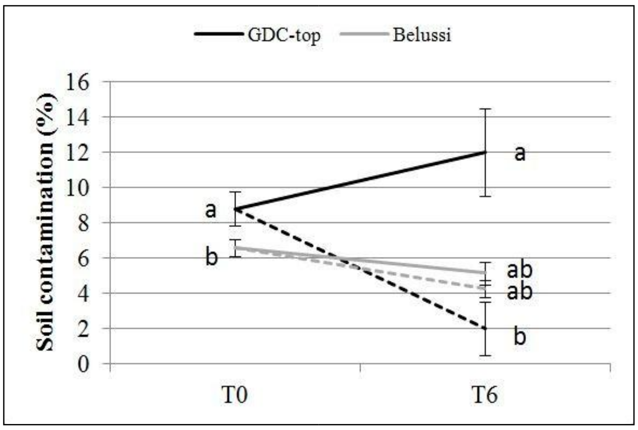

Figure 7. Mean (±SE) percentage of soil contamination before (T0) and after storage (T6) in GDC and Bellussi piles. Whole lines indicate the lower sector, while dotted line indicates the upper sector. Within each time, different letters indicate a significant difference at the level of $p \leq 0.05$ after Tuckey's test.

These results show that in the pile of GDC the soil moved in a quite effective way from the upper layer to the lower, but an evident soil loss from the pile was not identified. On the contrary, even if in a small quantity, the pile of Bellussi exhibited an effective soil loss. As storage conditions and piles dimension were similar and the stumps harvested with the same system, these differences can be attributed to the different morphology of the roots, which probably created a different internal structure in the two piles. Anerud and Jirjis [9], observed as the harvesting system affected the structure of the stump and as this, in turn, influenced other parameters like contamination and ash content. In the same study, according to the harvesting system, the final product had a different shape (cylindrical stump mass, with few lateral roots, or split stumps with some roots attached) that resulted in a different surface of the exposed area. Therefore, also in our study the morphology (size of the stump, shape, presence of more or less lateral roots) between the GDC and Bellussi modified the amount of the adherent soil, its exposition to the climatic variable, and hence the dynamics of the soil movement
within the pile.

The soil contamination has influence on the ash content of the stumps [11,14,15]. As reported by Uri et al. [15], the ash content in stump wood is extremely variable (1–24%) and often depend from the type of soil or the amount of precipitations. The vineyard stump analyzed after storage showed an ash percentage remarkably lower respect to that of the material analyzed immediately after the extraction, passing from 11.4% to 5.6% in the GDC stumps and from 22.4 to 13.7 in Bellussi stumps. The after-storage heating value of GDC and Bellussi roots was respectively 2.9% and 6.4% higher respect the before-storage samples (Table 1). However, it must be noted that fuel quality parameters were not analyzed per layers, as done for the study of the soil contamination. Therefore, data must be interpreted taking into account the fact that this average values may have changed if fuel quality parameter would have been studied separating the upper and the lower layers of the stacks.

Table 1. Ash content and heating value in GDC and Bellussi stumps immediately after the extraction (T0) and after high pressure water cleaning (T6).

Fuel Parameter	Stump	GDC	Bellussi
Ash (% dry weight)	T0	11.4	22.4
-	T6	5.6	13.7
Δ (%)	-	−51.9	−39.9
HHV * (MJ·kg^{-1} DW)	T0	17.1	15.4
-	T6	17.6	16.4
Δ (%)	-	2.9	6.4

* HHV: Higher Heating Value.

4. Conclusions

As modern fruit orchards tend to be intensively cultivated and super-exploited, the productive cycles of the plants are getting shorter, requiring frequent turnover. The eradication of unproductive plant stumps in end-life orchards is a costly operation and the scarce quality of the biomass due to high MC and soil contamination makes this material useless in any bio-energy conversion process. The present work has demonstrated that the combination of effective extraction technologies and low cost storage solutions, directly utilized at farm level, could be adapted to increase the quality of the stump, reducing the MC of the biomass and facilitating a natural cleaning process. In particular, the reduction of biomass MC was significant in both piles, passing from 52% to 12.4% in Bellussi and 11.5% in GDC. Regarding soil contamination, an effective cleaning due to storage was noted only in Bellussi rootstock pile, while the GDC pile experienced a soil migration from the upper layer to the lower. Nonetheless, as soil tended to accumulate in the lower part of the pile, it is expectable that using metal grids lifted from the ground would facilitate the cleaning process of the biomass. Finally, it must be pointed out that the storage at the farm site would be beneficial also for the organization of the logistic at the power plants, because the material recovery could be scheduled in a gradual way, avoiding congestions at the storage site of the plant itself.

Acknowledgments: This work was supported by the Italian Ministry of Agriculture and Forestry under the Suscace Project (Scientific support for the agriculture conversion to energy crops).

Author Contributions: L.P. and A.S. conceived and designed the experiments; L.P., V.A. and A.S. performed the experiments; E.S. analyzed the data; L.P. and F.G. contributed reagents/materials/analysis tools; A.S. and S.B. wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Gonzalez-García, S.; Dias, A.C.; Clermidy, S.; Benoist, A.; Maurel, V.B.; Gasol, C.M.; Gabarell, X.; Arroja, L. Comparative environmental and energy profiles of potential bioenergy production chains in Southern Europe. *J. Clean. Prod.* **2014**, *76*, 42–54. [CrossRef]
2. Brosowski, A.; Thrän, D.; Mantau, U.; Mahro, B.; Erdmann, G.; Adler, P.; Blanke, C. A review of biomass potential and current utilisation—Status quo for 93 biogenic wastes and residues in Germany. *Biomass Bioenergy* **2016**, *95*, 257–272. [CrossRef]
3. Bridgwater, T. Biomass for energy. *J. Sci. Food Agric.* **2006**, *86*, 1755–1768. [CrossRef]
4. Gominho, J.; Lourenço, A.; Miranda, I.; Pereira, H. Chemical and fuel properties of stumps biomass from Eucalyptus globulus plantations. *Ind. Crops Prod.* **2012**, *39*, 12–16. [CrossRef]
5. Bauhus, J.; Aubin, I.; Messier, C.; Connell, M. Composition, structure, light attenuation and nutrient content of understory vegetation in a Eucalyptus sieberi regrowth stand 6 years after thinning and fertilization. *For. Ecol. Manag.* **2001**, *144*, 275–286. [CrossRef]
6. Taylor, A.R.; Victorsson, J. Short-term effects of stump harvesting on millipedes and centipedes on coniferous tree stumps. *For. Ecol. Manag.* **2016**, *371*, 67–74. [CrossRef]
7. The Research Agency of the Forestry Commission. *Stump Harvesting: Interim Guidance on Site Selection and Good Practice*; Forest Research: Farnham, UK, 2009; pp. 1–18.
8. Kataja-aho, S.; Smolander, A.; Fritze, H.; Norrgard, S.; Haimi, J. Responses of soil carbon and nitrogen transformations to stump removal. *Silva Fenn.* **2012**, *46*, 169–179. [CrossRef]
9. Anerud, E.; Jirjis, R. Fuel quality of Norway spruce stumps—Influence of harvesting technique and storage method. *Scand. J. For. Res.* **2011**, *26*, 257–266. [CrossRef]
10. Picchio, R.; Verani, S.; Sperandio, G.; Spina, R.; Marchi, E. Stump grinding on a poplar plantation: Working time, productivity, and economic and energetic inputs. *Ecol. Eng.* **2012**, *40*, 117–120. [CrossRef]
11. Anerud, E.; Jirjis, R.; Gebresenbet, G. Cleaning of harvested Norway spruce stumps using a vibration-based method. *Int. J. For. Eng.* **2012**, *24*, 121–128. [CrossRef]
12. Johansson, T.; Hjelm, B. Stump and root biomass of poplar stands. *Forests* **2012**, *3*, 166–178. [CrossRef]
13. Laitila, J.; Nuutinen, Y. Efficiency of Integrated Grinding and Screening of Stump Wood for Fuel at Roadside Landing with a Low-Speed Double-Shaft Grinder and a Star Screen. *Croat. J. For. Eng.* **2015**, *36*, 19–32.
14. Laurila, J.; Lauhanen, R. Moisture content of Norway spruce stump wood at clear cutting areas and roadside storage sites. *Silva Fenn.* **2010**, *44*, 427–434. [CrossRef]
15. Uri, V.; Aosaar, J.; Varik, M.; Becker, H.; Kukumägi, M.; Ligi, K.; Pärn, L.; Kanal, A. Biomass resource and environmental effects of Norway spruce (*Picea abies*) stump harvesting: An Estonian case study. *For. Ecol. Manag.* **2015**, *335*, 207–215. [CrossRef]
16. Tylek, P.; Pietrzykowski, M.; Walczyk, J.; Juliszewski, T.; Kwas´niewski, D. Root Biomass and Morphological Characterization of Energy Willow Stumps. *Croat. J. For. Eng.* **2017**, *381*, 47–54.
17. Picchi, G.; Spinelli, R. Sradicatore Gottardo all'opera per fare biomassa da espianti. *Inf. Agrar.* **2012**, *40*, 27–30.
18. Picchi, G.; Pari, L.; Scarfone, A.; Barontini, M.; Spinelli, R. Unearthing the hidden resource: Biomass from rootstock recovery. *Biofuels Bioprod. Biorefin.* **2016**, *10*, 270–280. [CrossRef]
19. Persson, T. Tree stumps for bioenergy—Harvesting techniques and environmental consequences. *Scand. J. For. Res.* **2012**, *27*, 705–708. [CrossRef]
20. Barontini, M.; Scarfone, A.; Santangelo, E.; Gallucci, F.; Spinelli, R.; Pari, L. The CRA-ING experience on storage of poplar wood chip. In Proceedings of the 21st European Biomass Conference and Exhibition, Copenhagen, Denmark, 3–7 June 2013.

21. Lehtikangas, P.; Jirjis, R. Storage of logging residues in bales. In Proceedings of the 10th European Conference on Technology Exhibition, Biomass for Energy and Industry 1998, Wurzburg, Germany, 8–11 June 1998; pp. 1013–1016.
22. Walmsley, J.D.; Godbold, D.L. Stump Harvesting for Bioenergy—A Review of the Environmental Impacts. *For. Int. J. For. Res.* **2010**, *83*, 17–38. [CrossRef]
23. Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto (ARPAV)—Servizio Osservatorio Suoli e Rifiuti. Carta dei Suoli della Provincia di Treviso 2008. Available online: http://ows.provinciatreviso.it/suoli/map.phtml (accessed on 27 October 2017).
24. International Organization for Standardization. *ISO 16586:2003 Soil Quality—Determination of Soil Water Content as a Volume Fraction on the Basis of Known Dry Bulk Density—Gravimetric Method*; International Organization for Standardization: Geneva, Switzerland, 2003.
25. International Organization for Standardization. *ISO 18134-2:2015 Solid Biofuels—Determination of Moisture Content—Oven Dry Method—Part 2: Total Moisture—Simplified Method*; International Organization for Standardization: Geneva, Switzerland, 2015.
26. International Organization for Standardization. *ISO 18134-2:2017 Solid Biofuels—Determination of Moisture Content—Oven Dry Method—Part 2: Total Moisture—Simplified Method*; International Organization for Standardization: Geneva, Switzerland, 2017.
27. International Organization for Standardization. *ISO 18122:2015 Solid Biofuels—Determination of Ash Content*; International Organization for Standardization: Geneva, Switzerland, 2015.
28. International Organization for Standardization. *ISO/DIS 18125:2015 Solid Biofuels, Determination of Calorific Value*; International Organization for Standardization: Geneva, Switzerland, 2015.
29. Civitarese, V.; Spinelli, R.; Barontini, M.; Gallucci, F.; Santangelo, E.; Acampora, A.; Scarfone, A.; Del Giudice, A.; Pari, L. Open-Air Drying of Cut and Windrowed Short-Rotation Poplar Stems. *Bioenergy Res.* **2015**, *8*, 1614–1620. [CrossRef]

BEST AVAILABLE TECHNOLOGIES TO HARVEST CEREAL CHAFF

L. Pari, V. Alfano*, A. Scarfone, S. Bergonzoli, A. Suardi
Council for Agricultural Research and Economics, Research Center for Engineering and Agro-Food Processing (CREA-IT)
Via della Pascolare, 16. 00015 Monterotondo (Rome) - ITALY
*Corresponding author: Vincenzo Alfano, vincenzo.alfano@crea.gov.it.

ABSTRACT: This work has been developed under the AGROinLOG Project, "Demonstration of innovative integrated biomass logistics centres for the Agro-industry sector in Europe". An Integrated Biomass Logistics Center (IBLC), is based on the introduction of new production chains into existing agro-industries by using new biomass feedstock. The AGROinLOG Project dedicates great attention to investigate the potential of cereal chaff as a valuable resource. Made up of glumes, seed husk and rachis, it is valuable for animal feed or litter, or as feedstock for energy purposes. During cereal threshing, it is commonly left on the ground together with other thinner part of the cereal stems, whole or cracked kernels and weed seeds. Due to its value, many machineries builders has recently developed several systems for its recovery. The study represents a detailed and accurate survey of the harvesting technologies available at present in the market.

Keywords: threshing residues, combine harvester, straw baling, weed seeds, energy purposes, animal feeding

1 INTRODUCTION

The development of bio-economy has increased the biomass demand. Consequently, there is a competition for biomass utilization for food, feed, chemical and energy purposes [1]. The European policy for energy encourages the utilization of agro-forestry residues, limiting the energy crops plantations [2,3]. In this scenario, it is crucial to exploit the potential of biomass resources that are currently unexploited [4].

Among the agricultural residues, cereal chaff has gained interest due to their availability and properties both for energy purposes and for animal feeding [5, 6]. Moreover, from agronomic point of view, the collection of the chaff reduces the weed seed stock in the soil avoiding the herbicide treatments [7].

According to European yearly grain production, more than 50 Mt of chaff could be collected [8]. However, such resource is generally left on the ground after cereal threshing.

During the seed cleaning in the combine harvester, the chaff together with other fine residues (such as, short straw, damaged seeds and weed seeds) is retained by the sieves underneath the straw walkers and is blown to the rear of the combine.

Usually, this material is simply left to fall on the ground, and covered by the straw. The layer in direct contact with the ground cannot be collected with the pick-up in the following baling operation.

However, the growing interest in the exploitation of these residues both for energy (combustion, biogas) and for animal husbandry (fodder, litter), and also the need to reduce the load of seeds of resistant weeds (in the case of organic farming), has pushed some constructors to develop systems for the recovery of the chaff, separately or together with the straw.

The present review shows the main chaff collection technologies available on the market that, basically, implement the following mechanical chains:

- Chaff discharged on the top or inside of the straw swath for baling all together in a second time.
- Chaff discharged to an integrated back container, while straw can be both baled or spread on the ground.
- Chaff discharged to a towed trailer or no-stop baler.

The first method of collection can be preferred when biomass is used for energy production. In fact, baling the straw and chaff together, increases the amount of total biomass collected per hectare and the bales density [9].

On the other hand, collecting chaff separately from straw allows to obtain a product with an higher nutritive value than straw, suitable for husbandry feeding.

2 AVAILABILITY AND CHARACTERISTICS OF CEREAL CHAFF

Chaff is made up of seed glumes, seed husk and rachis (Figure 1).

Figure 1. Wheat chaff

During cereal threshing, the chaff is normally dispersed in the field together with straw and other fine residues retained by the combine sieves, such as unthreshed heads, short straw, leaf material, weed seeds and whole or cracked kernels from the harvested crop.

This material can be estimated in about 7% of the threshed product (40% are seeds, 48% straw, 5% stubble) (Figure 2).

According to EUROSTAT, more than 300 Mt grain is harvested yearly in EU28 [10] and considering a mean chaff to grain ratio of 0.17, more than 52 Mt yr^{-1} could be available to be collected in Europe [8].

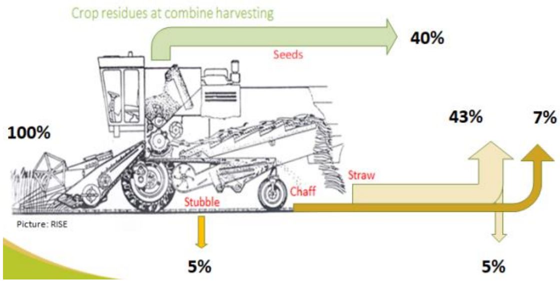

Figure 2. Material balance of cereal harvesting

3 MECHANICAL SOLUTIONS FOR CHAFF RECOVERING

Currently, several solutions for chaff harvesting are available on the market, and other are still at prototype stage. Conceptually, they are based on two management methods:

- collection of chaff together with straw;
- collection of chaff separately from straw.

In the first case, the chaff is discharged either above the straw swath or inside it, in order to be recovered in a second time by a baler together with the straw, increasing by 20-25% the total biomass collected.

In the separate collection, the chaff is delivered to dedicated collection systems, such as trailers towed by a tractor or by the combine itself, integrated containers in the rear of the combine, non-stop baling systems.

Both management methods implement different chaff delivery systems, including: augers, blowers, conveyor belts. The combination of management methods and delivery systems determine different mechanical solutions that can be summarized as following:

1. Windrowing systems
2. Blower systems
3. Systems with conveyor belt and chaff cart
4. Dedicated back container systems
5. One pass harvest and baling systems
6. Modified chaff spreader systems

3.1 Windrowing systems

The windrowing systems, preferred when using large harvesting heads, consist of kit mounted in the rear part of the combine harvester. It provides the collection of the chaff directly from the sieves, the lifting of the material by means of a augers system, followed by the releasing on the top of the windrow. In this way, the chaff forming a layer on the straw swath can be baled together with it, avoiding any contact with the ground.

The French manufacturer Thierart[4] proposes two types of kit based on this principle, to be applied to different models of combine harvesters.

With the kit specifically developed for the New Holland CR combine, the chaff is discharged on the straw windrow through a slide (Figure 3), while for other brand, through a removable hatch (Figure 4).

As an alternative to the recovery of the chaff, both kit foresee the evenly spreading of the chaff on the field for its following burying. In the first case, by lifting the slide and conveying the chaff towards the ventilation system, while in the second by activating a hydraulic deflector placed under the hatch.

[4] https://www.menuepaille.fr

Figure 3. Thierart windrowing system for NH CR combine and schematic representation

Figure 4. Thierart windrowing system for Claas Lexion combine and schematic representation

3.2 Blower systems

In these systems, the convey and delivery of chaff is provided by a combination of augers and turbines. A hopper placed under the sieves collects the chaff while an horizontal auger inside transports the material to the turbine. Then, the hydraulically driven turbine generates the cyclone for the expulsion of the material (Figure 5).

The French manufacturers Thierart and Thievin[5] adopt

[5] http://www.remorques-agricoles.fr/turbopaille-recuperateur-menues-pailles

such system with varying commercial proposals. The basic solution foresees the discharging of the product over the swath. Like in the windrowing systems, the chaff can be successively baled together with the straw. Otherwise, through the application of a rigid PVC pipe, the product can be sent inside a trailer, while the straw is windrowed or spread on the ground.

The trailer can be towed by a tractor moving in a lateral side, or by the combine itself (solution adopted by the partnership between the French manufacturers Thievin and Agri-structures) (Figure 6).

Also in this case, the option for spreading chaff on the ground is provided. This solution consists in applying at the turbine a "V" shaped spreader instead of the PVC pipe: the chaff thrown at high speed against the spreader is dispersed uniformly on both sides.

Figure 5. Thievin turbine system with discharge on windrow and schematic representation

Figure 6. Thievin turbine system with discharge on a trailer towed by a tractor (up) and by the combine itself

The Canadian Redekop[6] and the Australian Trufab[7] manufacturers, propose a chaff blower combined with a cyclone. The chaff blower is the same blower used to blow chaff into trailing wagons. The system adds a cyclone at the end of the blower to drop chaff directly on the straw windrow, allowing the baling with the straw.

The cyclone reduces the air pressure, allowing the chaff to fall.

Figure 8. Trufab chaff cyclone and blower for transferring chaff to the top of the straw windrow

3.3 Systems with conveyor belt and chaff cart

Chaff carts are widely adopted among the Australian "Harvest weed seed control" (HWSC) practices. The carts, towed by the combine harvester, collect chaff and weed seeds escaping the harvester. In recent years the chaff delivery system changed from cross augers and blowers to a simple conveyor belt (Figure 6).

The conveyor belt system has proven to be more efficient compared to traditional chaff transfer systems requiring less power from the header.

It is possible to collect all of the material that comes out of the back of the combine harvester or spread the straw and just catch the chaff coming from the sieves.

[6] http://www.strawchopper.com/

[7] http://www.trufab.com.au/chaff-carts.html

Figure 6. Springfield Chaff Cart

3.4 Dedicated back container systems

The French manufacturers Thierart and Bionalan[8] produce dedicated containers to be applied on the combine harvesters of different brand. The system consists of a collection container, placed behind the combine harvester, capable to be filled with chaff, while straw is discharged on the ground. The structure can be rigid but heavier or made of tarpaulin inside a metal chassis.

During the harvesting, the chaff fall into an hopper at the exit of the combine harvester and then transferred by means of two vertical screws in the dedicated box. Once filled, the residues are discharged at the edge of the field to be collected at a later time by a baler (Figure 7).

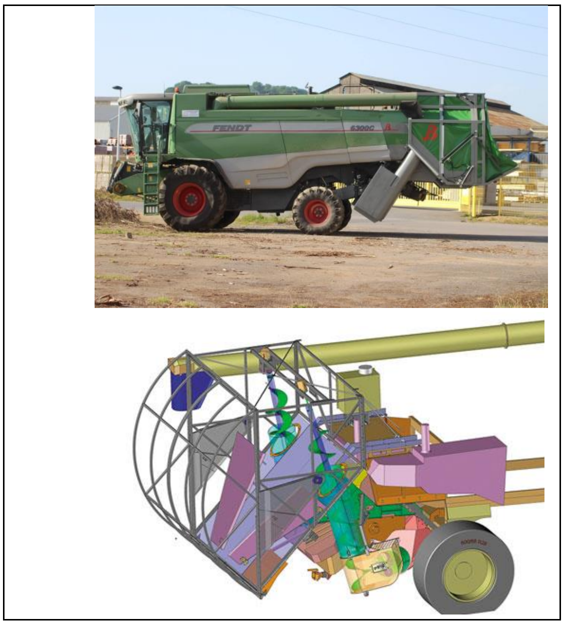

Figure 7. Bionalan back container and schematic representation

3.5 One pass harvest and baling systems

This system allows to harvest and bale the residues in one pass, avoiding the contact with the ground.

Thierart provides an interesting option that foresees the continuous pressing of the only chaff, simultaneously to the threshing (Figure 8). It consists of a modular system, made of a round baler connected to a 2 m^3 tank and a dedicated power system, towed by the combine harvester.

Figure 8. Thierart modular system for continuous pressing of the chaff during threshing

Similarly, the French company Perard[9] has developed a baling system for chaff, named VMP. Connected laterally to a combine harvester, the VMP sucks out the compressed chaff in the form of cylindrical boots 20 times denser. The system, still in the prototype stage, is automated with a control console in the combine harvester's cab and has its own power source from an integrated diesel engine.

Figure 11. Perard VPM system

Hillco Technologies[10], has developed a single pass baling system for straw and all other thrashing residues.

The materials from the rear of the combine are blown into a hopper which is attached to the front of a standard John Deere round baler (Fig. 9)

Figure 9. Hillco Single Pass Round Bale System for John Deere

The Australian Glenvar[11] sells the Bale Direct System

[8] https://www.bionalan.fr/nos-produits/recuperateur-de-menue-paille

[9] https://www.perard.fr

[10] http://www.hillcotechnologies.com/sprb-systems.html

[11] http://www.glenvarbaledirect.com.au/

which provides single-pass harvest and baling of threshing residues using a large square baler linked directly to the combine by a drawbar attached to the main front drive axle. Residue from the combine is fed directly into baler via a conveyor belt. The power to drive the baler comes from a hydraulic pump mounted on the combine.

Figure 10. Glenvar Bale Direct System

3.6 Modified chaff spreader systems

The Swedish manufacturer Rekordverken[12] has developed a system, named "Combi", that allows the management of straw and chaff together or separately, through the spreading in the field or the recovery of the two products. In fact, the chaff spreader can be adjusted to throw alternatively the chaff on the combine sides or towards the straw chopper. Then, by activating or deactivating the straw chopper, four combinations in total are obtainable as follows:

- Chaff spreader activated / Straw chopper deactivated: unloading of the straw in the swath for the subsequent baling together with the chaff, which is thrown by the chaff spreader inside the straw flow (Fig. 10A);

- Chaff spreader deactivated / Straw chopper deactivated: the straw is windrowed but chaff is not mixed in the straw flow, so it is left to be laterally dispersed (Fig. 10B).

- Chaff spreader activated / Straw chopper activated: straw and chaff go together inside the straw chopper and are spread for the entire working width of the machine. (Fig. 10C).

Chaff spreader deactivated / Straw chopper activated: straw is chopped and spread but chaff is left to be laterally dispersed (Fig. 10D).

The first combination, preferred for energy purposes, has the objective of maximizing the quantity of material to baling. The second one is chosen in order to collect less dusty straw as bedding material (straw without chaff).

The third distribution option allow to chop all residues together distributing the mixed organic matter to the ground.

The last option guarantees the separate management of the two residues and avoids overloading the straw chopper.

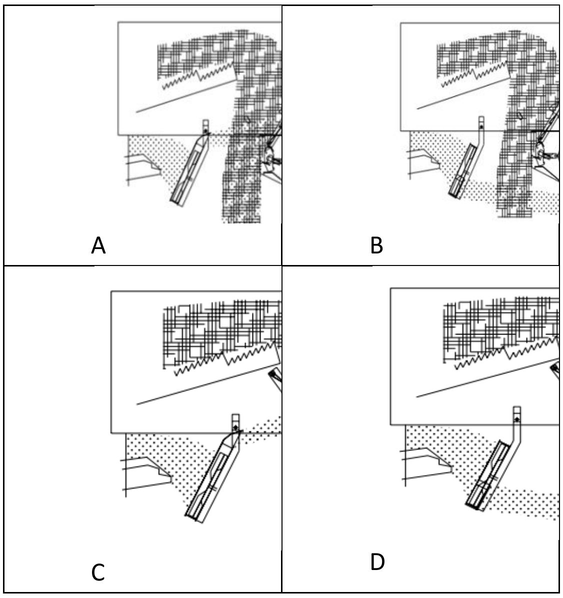

Figure 10. Four combinations for the Rekordverken Comby System

4 CONCLUSIONS

The survey, though accurate, has revealed the existence of a limited number of manufacturers that offer mechanical solutions for the recovery of the chaff (Table II).

In general, the solutions that provide for the discharge on the swath (windrowing system or turbine system) or inside it (modified chaff spreader), have a limited investment cost, are easily adaptable to all types of combine harvester and they don't influence the harvesting performance (working time). On the other hand, the collection of the chaff together with the straw offers fewer options for its exploitation, mainly energy production.

On the contrary, the separate collection allows a greater range of possible destinations for chaff and straw. However, in systems that use trailers for chaff recovery (turbine systems with trailer and chaff-cart) and in one pass harvest and baling systems, the less manoeuvrability, has a negative effect on working time. Moreover, these solutions are more expensive.

Pros and cons of each technology are showed in the Table I.

Table I. Pros and cons of each technology analysed

System	Pros	Cons
Windrowing	- Harvester performance unmodified - Adaptability to all models of combine	- Valorisation of chaff mainly for energy - Possible chaff losing in raining conditions

[12] http://www.rekordverken.se/

	- Low investment	
Turbine / discharging on the swath	- Harvester performance unmodified - Adaptability to all models of combine - Low investment	- Valorisation of chaff mainly for energy - A hydraulic adaptation is required - Possible chaff losing in raining conditions
Turbine / discharging on a trailer	- The separate collection allows a greater range of possible valorisation for chaff and straw	- Worst manoeuvrability - Risk of clogging (pipe) in raining conditions - PVC pipe wear
Conveyor belt and chaff cart	- Less energy consumption comparing to auger and turbine delivery systems	- Possible chaff losing in windy conditions (the goal is the collection of seed weeds)
Dedicated back container	- Adaptability to all models of combine - High collection of seed weeds - Autonomy (discharging at field-edge)	- Higher costs - Overhang and weight on the rear axle - Risk of dirt under piles
One pass harvest and baling	- Overall working time	- High costs
Modified chaff spreader	- Harvester performance unmodified - Little extra maintenance - Original manufacturer's equipment - Ease to activate / deactivate the system - Low investment	- No separate collection - Possible chaff losing

Table II. List of the manufacturers mentioned in this survey and their solutions

Manufacturer	**Collection of chaff together with straw**	**Separate collection**
Thierart	Chaff on the swath (chutes/hatch/turbine) One pass harvest and baling (turbine)	Chaff into - towed trailers (turbine) - back containers (auger systems)
Thievin	Chaff on the swath (turbine)	Chaff into towed trailers (turbine)
Rekordverken	Chaff inside the swath (modified chaff spreader)	None
Redekop	Chaff on the swath (blower combined with a cyclone)	Chaff into trailers (blowers)
Trufab	Chaff on the swath (blower combined with a cyclone)	Into chaff carts (blower / conveyor belt)
Bionalan		Chaff into back containers (auger systems)
Springfield		Into chaff carts (conveyor belt)
Hillco	Single pass round baling (blower)	
Glenvar	Single pass square baling (conveyor belt)	
Perard		Single pass baling (blower)

5 REFERENCES

[1] N. Scarlat, J.F. Dallemand, F. Monforti-Ferrario, V. Nita, The role of biomass and bioenergy in a future bioeconomy: Policies and facts, Environ. Dev. 15 (2015) 3–34. doi:10.1016/j.envdev.2015.03.006.IEA

[2] European Parliament, Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009, Off. J. Eur. Union. 140 (2009) 16–62. doi:10.3000/17252555.L_2009.140.eng.

[3] EU 2015/1513, ILUC Directive, Off. J. Eur. Union. (2015) 20–30. doi:http://eur-lex.europa.eu/pri/en/oj/dat/2003/l_285/l_28520031101en00330037.pdf.

[4] A. Paiano, G. Lagioia, Energy potential from residual biomass towards meeting the EU renewable energy and climate targets. The Italian case, Energy Policy. 91 (2016) 161–173. doi:10.1016/j.enpol.2015.12.039.

[5] Hutton, G. (2008). Increasing cow/calf profitability using chaff and chaff/straw feedstuffs. Alberta Agriculture and Forestry, Alberta Agri-facts. Agdex 420/50-2.

[6] R. Saidur, E.A. Abdelaziz, A. Demirbas, M.S. Hossain, S. Mekhilef, A review on biomass as a fuel for boilers, Renew. Sustain. Energy Rev. 15 (2011) 2262–2289. doi:10.1016/j.rser.2011.02.015.

[7] S.J. Shirtliffe, M.H. Entz, Chaff collection reduces seed dispersal of wild oat (Avena fatua) by a combine harvester, Weed Sci. 53 (2005) 465–470. doi:10.1614/WS-03-109R2.
[8] D.H. McCartney, H.C. Block, P.L. Dubeski, A.J. Ohama, Review: The composition and availability of straw and chaff from small grain cereals for beef cattle in western Canada, Can. J. Anim. Sci. 86 (2006) 443–455. doi:10.4141/A05-092.
[9] Lundin, G. & Rönnbäck, M. (2010) Simultaneous harvest of straw and chaff for energy purposes - Influence of bale density, yield, field drying process and combustion characteristics. Uppsala, JTI - Swedish. Institute of Agricultural and Environmental Engineering.
[10] EC, Eurostat Database, Eur. Comm. Online Stat. Database. (2017). http://ec.europa.eu/eurostat/data/database.

6 ACKNOWLEDGEMENTS

The work was performed in the framework of the European project AGROinLOG "Demonstration of innovative integrated biomass logistics centres for the Agro-industry sector in Europe".

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No 727961.

7 LOGO SPACE

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Equipping a combine harvester with turbine technology increases the recovery of residual biomass from cereal crops via the collection of chaff

Alessandro Suardi[1], Walter Stefanoni[1]*, Vincenzo Alfano[1], Simone Bergonzoli[2] and Luigi Pari[1]

1 CREA Research Centre for Engineering and Agro-Food Processing. Via della Pascolare, 16, Monterotondo (Rome), ITALY
2 CREA Research Centre for Engineering and Agro-Food Processing. Via Milano, 43. 24047 Treviglio (BG) - ITALY
* Correspondence: walter.stefanoni@crea.gov.it; Tel.: +39 0690675205

Received: date; Accepted: date; Published: date

Abstract: In cereal crops, chaff is a valuable lignocellulosic by-product that accounts for more than 50 Mt y^{-1} in Europe and is suitable for bioenergy purposes. Chaff is usually not collected due to the lack of combine harvesters that have the capability to handle it properly. The present two years experimental study investigated the hypothesis that the overall biomass collected in wheat crop can be increased by equipping the combine harvester with an aftermarket device. Chaff, discharged from the combine harvester-cleaning system, is collected by the turbine that delivers it either on the swath or on a lateral trailer towed by a tractor. The performance of all machines involved in the harvesting (combine harvester, tractor, baler, and trailer) were assessed. The chaff was collected in bales with the straw (A mode) and separately on a trailer (C mode). Comparisons with non-collected treatment (B mode) were performed in order to estimate the total chaff collected and the biomass losses. The results showed that 1.79 t FM ha^{-1} per year of chaff could be collected when baled with the straw, whereas 1.27 t FM ha^{-1} were collected separately on a trailer. Both field and material capacity were not negatively affected by the chaff collection. Therefore, our study confirmed the hypothesis that turbine technology is a valid solution for increasing the total residual biomass collected in cereal cropping for energy purposes.

Keywords: wheat; straw; weed seed; biocommodity; threshing; bioenergy

1. Introduction

The development of bioeconomy of last years has increased the biomass demand not only for energy purposes but also for chemicals and material applications [1]. The European policy for energy encourages the utilization of agroforestry residues, limiting the energy crops plantations [2]. Moreover, traditional sources for bioenergy production would not be enough to meet the future energy needs and to respond to the new targets of EU 2030 framework for climate and energy policies [3,4]. In this scenario, it is crucial to exploit biomass resources that are currently unexploited such as agricultural residues [5].

Among the agricultural residues, cereal chaff has gained interest due to its availability and properties. Chaff is commonly defined as the by-product of cereal harvest comprehensive of glumes, hulls, short straw, damaged kernels and weed seeds. During threshing, the chaff fraction sieved by the cleaning shoe underneath the straw walkers is blown to the rear of the combine harvester [6]. This material is normally either left to fall on the ground below the straw swath or spread. In both cases the chaff cannot be collected by the pick-up in the following baling operation.

According to EUROSTAT, about 138 Mt of wheat and spelt are harvested yearly in EU28 [7]. Considering a mean value of chaff to grain ratio of 0.17 [8], more than 23 Mt yr^{-1} of chaff is available and harvestable in Europe. However, such resource is generally left on the ground after cereal threshing and lost.

Nevertheless, chaff could be a valuable source for an energetic utilization either when baled with straw [9] or pelleted after being separated from the straw [10]. Moreover chaff can be a valuable feedstocks in a second generation bioethanol process [11].

Although cereal straw and chaff are of low nutritive value they have the potential to be a substantial feed resource for beef cows [8] as a hay substitute in winter feeding [12] . However, the main use of straw in animal farming is for littering but since combining has taken over manual trashing, the chaff is no longer included into the straw. The lack of absorbent capacity provided by chaff has dictated the reduction in straw usage as natural bedding for feedstock. In fact, unless the use of specific equipment, chaff is usually lost by combines in the field and incorporated into the soil during the preparation of the field for following year crop [13]. However, the incorporation of residual organic matter, particularly the chaff, is also reported to be correlated to root diseases and Pythium spp. populations that result in root system damages in the new seedlings [14].

On the other hand, agronomic advantages are also experienced when chaff is removed. In fact, he collection of the chaff during cereal harvesting can reduce the weed seed stock in the soil by removing weed seeds before they are returned to the field [15]. The recognition that at grain harvest the seeds of important crop weeds are intact and attached to the upright plant and can be ''harvested'' led to the introduction in Australia of the Harvest Weed Seed Control (HWSC) systems [16]. The most widely adopted system is the narrow windrow burning. It consists of a grain harvester mounted chute to concentrate all the exiting chaff and straw residues into a narrow-windrow that are subsequently burnt. In order to avoid in-situ burning, other methods are currently used, namely: Chaff Cart consists of a wagon towed by the combine that collects the chaff exiting the trashing system and temporarily accumulate it in the bin for the discharge when full; Bale Direct Systems (BDS) are large square balers directly attached to the harvester that make bales from the chaff and straw residues exiting the grain harvester; Harrington Seed Destructor (HSD) uses a cage mill mounted on a trailer to crush the weed seed carried by the chaff flow [17,18].

Recently, with the aim to face the herbicide-resistant weeds, Klaus Jakobsen and Christoph Glasner et al. (2019) [19,20] investigated if hot exhaust gas from a combine harvester could be used to reduce germination or kill weed seeds during the harvesting process in order to develop an integrated system in the combine harvester.

On the contrary, the growing interest in the exploitation of these residues for industrial uses has pushed some constructors to develop systems for the recovery of the chaff. Currently, several solutions for chaff harvesting are available on the market, and other are still at prototype stage [21].

Conceptually, they are based on two management methods: collection of chaff together with straw and collection of chaff separately from the straw. In the first case, chaff is discharged either on top or inside of the straw swath then baled together with the straw. In the separate collection method, the chaff is delivered to dedicated collection systems, such as: trailers towed by a tractor or by the combine itself or integrated containers in the back of the combine or non-stop baling systems. These management methods implement different chaff delivery systems, including: augers, blowers and conveyor belts. The combination of management methods and delivery systems determine different mechanical solutions that can be summarized as following: windrowing systems; turbine systems; dedicated back container systems; one pass harvest and baling systems; modified chaff spreader systems.

Due to the recent gain of interest in chaff collection, there is a limited number of agricultural machine constructors that offer mechanical solutions for the recovery of the chaff. In general, the solutions provided for the discharge on the swath (windrowing system or turbine system) or inside the swath (modified chaff spreader), have a limited investment cost, they are easily adaptable to all types of combine harvester without influence the harvesting performance (working time).

On the contrary, the separate collection would allow a wider range of possible uses of chaff and straw and possible higher market prices as well. However, the chaff recovery systems like turbine systems with trailer and chaff-cart or one pass harvest and baling systems could have negative effects on the machines maneuverability with possible increase of the working time and so a reduction of the harvesting performance. Besides, these solutions imply higher purchasing costs [21].

Due to a lack of scientific data about the chaff collection feasibility, performance and quality of the work carried out by the machine available on the market, during the H2020 AGROinLOG project [22], CREA carried out straw and wheat chaff harvesting tests in Le Faulx (Pannecè, France) using a combine harvester equipped with the turbine system, named "Turbopaille", developed by the French company Thievin. The wheat residue harvesting tests were carried out in July 2018 and July 2019, aimed to quantify the amount of residue potentially collectable (chaff and straw), the machines performance, fuel consumption of all machines involved in the harvesting chain, as well as the potential yield of seeds, straw and chaff and the losses in two years experiment.

2. Materials and Methods

2.1 Field test and crop characteristics

The two-years tests were carried out both on the same field in Le Flaux (Pannecè, France) (47°29'16.4"N 1°13'26.1"W). The sowing of wheat took place in the 43rd week in both years at the density of 225 kg ha^{-1}, a 50% blend of two cultivars was used: Absalon and Syllon. In both years, the same regime of fertilization and pest control was followed. The harvest in 2018 was performed during the 29th week while in 2019 in the 30th. During the week before the harvest, a homogeneous area of about 6 ha was selected and delimited to perform the tests.

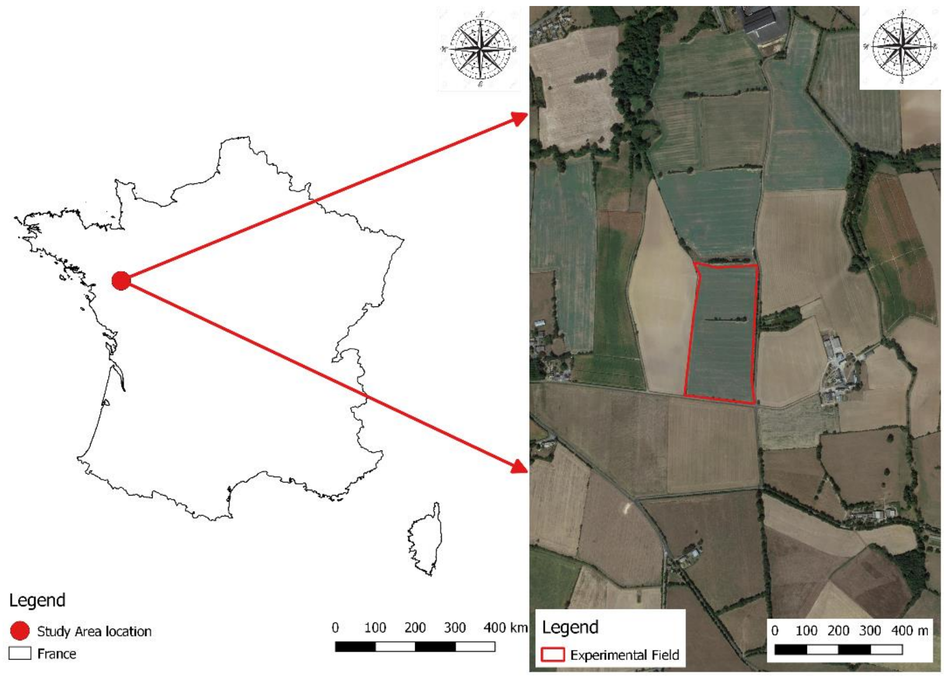
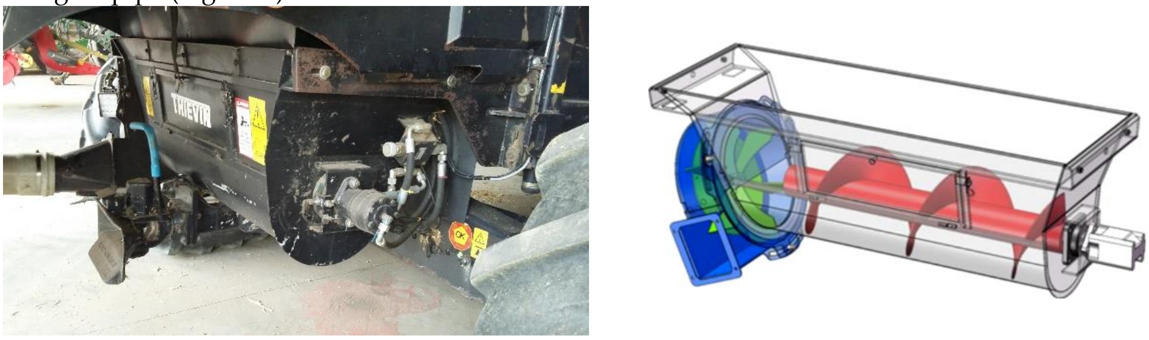


Figure 1. Study area location and field test

2.2 Thievin system description

The Thievin system for chaff recovery, named "Turbopaille" [23], is mounted in the rear part of the combine harvester. It has a dedicated tank provided with and endless screw which pushes the chaff in the inlet of a turbine. Here, the turbine increases the pressure of the air and the chaff is forced out through a pipe (Figure 2).



(a) (b)

Figure 2. (a) Thievin system "Turbopaille" for chaff collection and (b) schematic representation

The Thievin system can work in three different arrangements: discharging of the chaff over the straw swath (A Mode); spreading of the chaff by applying a "V" shaped spreader (B Mode); chaff discharging by PVP pipe on a trailer towed by a tractor side-by-side the combine harvester (C Mode) (Figure 3).

(A)

(B)

(C)

Figure 3. Thievin system working arrangements: unloading of the chaff on the straw swath (A); chaff spreading mode (B); unloading of the chaff on a trailer (C)

In 2018 only A mode (chaff on the swath) and B Mode (chaff spreading) were tested, while in 2019 also the C Mode (discharge on trailer) was analyzed. In the two years experiment all machines were the same except the combine. However, the setting and the drivers were the same in all machines (Table 1).

Table 1. Equipment used during the tests

Harvesting phase	**2018**	**2019**
Seed threshing	Combine: New Holland CX840 Thievin system: A and B mode	Combine: New Holland CX8.70 Thievin system: A, B and C mode
Biomass baling	Tractor: Deutz-Fahr Agrotron M620 Baler: Deutz-Fahr Varimaster 690	Tractor: Deutz-Fahr Agrotron M620 Baler: Deutz-Fahr Varimaster 690
Separate chaff collection	Not performed	Tractor: John Deere 8270R Trailer: Thievin Cortal 240

According to the working arrangements, the biomass discharged on the windrow and baled afterward, was made of: straw + chaff in A mode and only straw in both B and C mode. Therefore, the amount of chaff baled was calculated as difference between the total weight of biomass baled with system A and system B while the amount of chaff collected separately in C mode was weighted in the local farm scale.

2.3 Experimental design and pre-harvest sampling

In both years of testing, a split plot experimental designs were used. Before harvesting, the experimental field was divided in three blocks in order to have three replicates per treatment (2 treatments in 2018: A and B mode; 3 treatments in 2019: A, B and C mode) (Table 2). The width of each experimental unit (plot) was 4 times the combine header width, in order to assess the combine performance in 4 adjacent passes per plot (3 turning times). Total surface was about 4.2 ha (0.7 ha each plot) in 2018 and about 3.6 ha (0.4 ha on average each plot).

Table 2. Experimental design (2 treatments in 2018: A and B mode; 3 treatments in 2019: A, B and C mode)

Year	**Block 1**			**Block 2**			**Block 3**		
	Plot A1 chaff on swath	Plot B1 chaff spreading	Plot C1 chaff on trailer	Plot C2 chaff on trailer	Plot B2 chaff spreading	Plot A2 chaff on swath	Plot B3 chaff spreading	Plot A3 chaff on swath	Plot C3 chaff on trailer
2019	Y	Y	Y	Y	Y	Y	Y	Y	Y
2018	Y	Y	N	N	Y	Y	Y	Y	N

Y: test performed; N: test not performed.

The first pass of the combine in each side of the experimental field was not considered in order to avoid possible edge effects on the crop. One day before the combine harvesting, the whole plants of 10 samples areas of 1 m^2 each randomly chosen were hand harvested from the ground level. Stems and ears were weighed separately. Successively, all ears and a representative sample of stems were put in sealed bags and shipped to the laboratory of CREA for further measurements, as: theoretical yield of grain and chaff, dry weight and humidity content.

2.4 Harvesting tests

The harvesting tests concerned the threshing and the baling steps performed in each experimental unit (plot). Machines performance (working times and fuel consumption), grain and residues yield, moisture content and bulk density of biomass, were the parameters measured. Moreover, after harvesting, the average cutting height and the losses were assessed.

2.4.1 Machines performance

Working time study was performed according to the standards ASAE S496.2 [24]. The study of the working times allowed determining parameters such as the Effective Field Capacity (EFC) (ha h^{-1}) and the Theoretical Field Capacity (TFC) (ha h^{-1}).

The EFC of a farm machine is the rate at which it performs its primary function, i.e., in the case of the combine, the number of hectares harvested per hour. The EFC of a machine in the field can be easily calculated by dividing the hectares processed by the Operative Time (OT). The operative time is the time needed to complete the harvest, including accessory times, such as turning times and time needed for maintenance, regulations, refueling and unloading the hoppers. On the contrary, the TFC is the maximum possible field capacity without the accessory times. By knowing the yield of seeds and straw, it was possible to obtain also another good indicator of the machine performance called Material Capacity (MC), i.e., the quantity of grain or wheat residues harvested per time unit (t h^{-1}).

Fuel consumption of all the machines involved (combine and tractors) was calculated by refilling the tank at end of each plot. A graduated cylinder was used for the measurements of the volume of the fuel need per single operation.

2.4.2 Biomass yield and characterization

The total yield of grains, straw and chaff (collected separately in C Mode) per each plot was measured using the farm scale. After the harvesting, three samples of grain and residues were collected from all treatments for moisture content determination. Seeds and chaff bulk density were assessed in-situ according to the technical standard ISO 17828:2015 [25]. Per each treatment, 5 bales were randomly chosen and measured in weight and volume for the determination of the mean bulk density.

2.5 Post-harvest measurements

The average cutting height value of the of the combine header (height of the stubbles) was derived by averaging 100 measurements randomly taken in a diagonal transect selected on-field. The amount of biomass not harvested was assessed by cutting and weighting the stubbles from 10 sample areas (1 m^2 each) randomly chosen. Among them, five samples were collected for moisture content.

In the laboratory, kernels were first separated in a stationary thresher (Cicoria mod. Plot 2375) from the rest of the ears (chaff, rachis, lemma, glumes and palea). In addition to the residual material previously assessed in laboratory, the turbine technology allows to collect other kinds of light-weighted residuals produced by the cleaning mechanisms of the combine, such as: short straw, damaged seeds and weed seeds. On-field samples of the residuals produced by the Thievin system were further investigated in order to estimate the contribution of the light-weighted residuals to the total extra biomass collected. Dry weight and humidity content of stems, kernels and chaff was assessed according to the standard EN ISO 18134-2:2017 [26].

Seed, chaff and straw losses in each plot were assessed as difference between the theoretical yield of biomass estimated with the pre-harvest plots and the effective amount harvested.

2.6 Statistical analysis

The statistical analysis was performed in order to discriminate the differences among the treatments of the same year; while the comparison of the same treatment in the two years was not taken into account.

All data were subjected to the analysis of variance (ANOVA) using the R 3.6.1 software to separate statistically different means ($P \leq 0.05$). Tukey's HSD post-hoc test was performed to calculate the statistical differences between the means.

3. Results and discussion

3.1 Combine performance

Apart from the MC (that was affected by different yield in the two years), the performance of all the machines involved in the treatments in both years were similar (Table 3). In fact, the combine performance was not influenced by the working arrangements contrary to hypothesis speculated by Unger & Glasner, (2019) [27]. The performance was not affected in C mode either where the combine harvester and tractor with the trailer had to work side-by-side. In facts, no statistical differences were found among the treatments.

Table 3. Combine performance in 2018 and 2019 according to working arrangements (treatments)

Treatment	Theoretical Field Capacity (ha h^{-1})		Effective Field Capacity (ha h^{-1})		Material capacity (t h^{-1})	
	2018	2019	2018	2019	2018	2019
A mode	2.57±0.13	2.56±0.01	2.24±0.11	1.98±0.02	13.98±0.13	17.27±0.56
B mode	2.71±0.09	2.61±0.06	2.41±0.10	2.04±0.06	14.39±0.13	17.25±1.13
C mode	np	2.69±0.12	np	2.03±0.11	np	17.10±0.77

np: not performed.

Combine harvester fuel consumption, measured only in 2019, was on average 21.63 l h^{-1} (46.7 l ha^{-1}), with no significant differences among treatments.

3.2 Baler performance

Considering the baling phase, statistically significant differences were found in the EFC (that includes accessories times, such as turning time and unloading time) and the MC between A and B modes in both years. Baling the swaths with higher biomass content (A mode: straw + chaff) was significantly slower than baling the swaths with less biomass (B mode: only straw) (Table 4). No differences were found when chaff was collected separately on the trailer (C mode). In 2019 the TFC, EFC and MC were lower than 2018 due to the higher biomass yield.

Table 4. Baler performance in 2018 and 2019 according to treatments (common letters within columns denote the absence of significant difference ($p<0.05$))

Treatment	Theoretical Field Capacity (ha h^{-1})		Effective Field Capacity (ha h^{-1})		Material Capacity (t h^{-1})	
	2018	2019	2018	2019	2018	2019

A mode	5.23±0.65	4.64±0.31	3.46±0.28 b	3.09±0.13 b	20.79±0.7 a	20.20±2.0 a
B mode	5.99±0.16	4.82±0.09	4.05±0.16 a	3.45±0.10 a	18.73±0.7 b	15.09±0.7 b
C mode	np	4.93±0.13	np	3.33±0.09 ab	np	19.16±2.5 ab

np: not performed

In 2018 the fuel consumption during baling was not affected by the treatments. On the contrary, the tests repeated in 2019 showed a higher fuel consumption during the baling in treatment A respect to the others (Table 5). It was about double when analysed in relation to the surface (l ha^{-1}) and the time (l h^{-1}). Considering the biomass baled (l t^{-1}), such result was found only in comparison with treatment C, while no statistical differences were found with treatment B (Table 5).

Table 5. Baler fuel consumption in 2018 and 2019 according to treatments (common letters within columns denote the absence of significant difference ($p<0.05$))

Treatment	Fuel consumption (l ha^{-1})		Fuel consumption (l h^{-1})		Fuel consumption (l t^{-1})	
	2018	2019	2018	2019	2018	2019
A mode	4.65±0.91	6.21±1.5 a	16.09±3.36	19.13±4.33 a	0.77±0.15	0.94±0.12 a
B mode	4.66±0.11	2.81±0.64 b	19.02±1.44	9.68±3.87 b	1.01±0.13	0.64±0.23 ab
C mode	np	2.43±0.94 b	np	8.04±2.90 b	np	0.41±0.09 b

np: test not performed

3.3 Biomass assessment

3.3.1 Yield

Productivity in 2019 was higher than in 2018. The total biomass estimated in pre-harvest plots was about 1.9 t ha^{-1} higher in 2019. The wheat ears were in both years 56 % of the total biomass (44 % straw), with the same repartition in the ears of seeds (about 78 %) and chaff (22 %) as showed by the laboratory threshing (Table 6).

Table 6. Theoretical biomass in wheat field assessed in 2018 and 2019

	Theoretical biomass (f.m.)	
Year	2018	2019
Total biomass (t ha^{-1})	16.76±1.44	18.69±1.77
Straw (t ha^{-1})	7.39±0.73	8.33±0.75
Wheat ears (t ha^{-1})	9.37±0.77	10.36±1.34
Seeds (t ha^{-1})	7.32±0.60	8.18±1.06
Chaff (t ha^{-1})	2.04±0.17	2.18±0.28

Although the agricultural protocol (see paragraph 2.1) was the same in both years, differences in the biomass yield were recorded. Consistently with the theoretical yield, in 2019 the seeds harvested were on average 1.8 t ha^{-1} higher than 2018. In both years, there were no statistically significant differences in seed yield among treatments (Table 7).

Table 7. Seed harvested according to treatments in 2018 and 2019

Treatment	Seed harvested (t f.m. ha^{-1})	
	2018	2019
A mode	6.26±0.19	8.15±0.32
B mode	6.04±0.06	7.85±0.40
C mode	np	7.87±0.10
Mean	6.17±0.21	7.96±0.30

np: not performed

Regarding the biomass collected, there were statistically significant differences between treatment A (bales made of straw + chaff) and B (only straw), confirming the contribution of chaff as additional biomass raising the total weight of biomass harvested. In fact, the difference between biomass baled in the two treatments allowed to assess the chaff baled, respectively 1.39 t ha^{-1} (30% extra biomass) in 2018 and 2.19 t ha^{-1} (50% extra biomass) in 2019 (Figure 4). Similar tests performed by INRA- *Institut National de la Recherche Agronomique* in the frame of the local project « Systèmes de Cultures Innovants» and CUMA - *Federation Nationale des Cooperatives d'Achat et d' Utilisation de Materiel Agricole* in 2011 and 2012 demodays with turbine systems, provieded lower mean results: respectively 1.5 t ha^{-1} and 1.15 t ha^{-1} [28,29].

Although the biomass baled in A was 0.78 t ha^{-1} higher than biomass baled in C, contrary to what was expected, there were no significant differences in baled biomass between treatment A and C (chaff on trailer tested only in 2019).

In treatment A, the effective additional biomass collected thanks to the Thievin system totally met the theoretical value of chaff estimated from the pre-harvest tests. On the other hand, the chaff collected in the trailer was 0.92 t ha^{-1} lower than the theoretical amount of chaff. In this case, the Thievin was required first to collect the chaff into the dedicated tank and then lift it for the discharge into the trailer. Therefore, in order to accomplish the second task, it is conceivable to hypothesize a higher demand in energy of the system: the intake rate of the chaff in the dedicated tank of Thievin system (Figure 2) was probably higher than its capacity to discharge it into the trailer, thus some chaff remained mixed with straw and then baled. In order to reduce these drawbacks in case of separate collections of chaff, the following considerations can be taken into account: increase the energy provided to the turbine, increase the diameter of the PVC pipe and eventually, decrease the biomass intake rate of the combine by either reducing the speed of the combine or using narrower header. In fact, the last strategy is also reported by French Company Thiérart which provides a similar Turbine technology for chaff collection. Specifically, Thiérart highlights that its device is suitable for combine headers measuring less than 5.5 m wide [30].

Nevertheless, 1.27 t ha^{-1} of chaff collected separately with C mode is close to the mean value of 1.3 t ha^{-1} and 1.5 t ha^{-1} reported respectively by CUMA and INRA using a back container system [28,29].

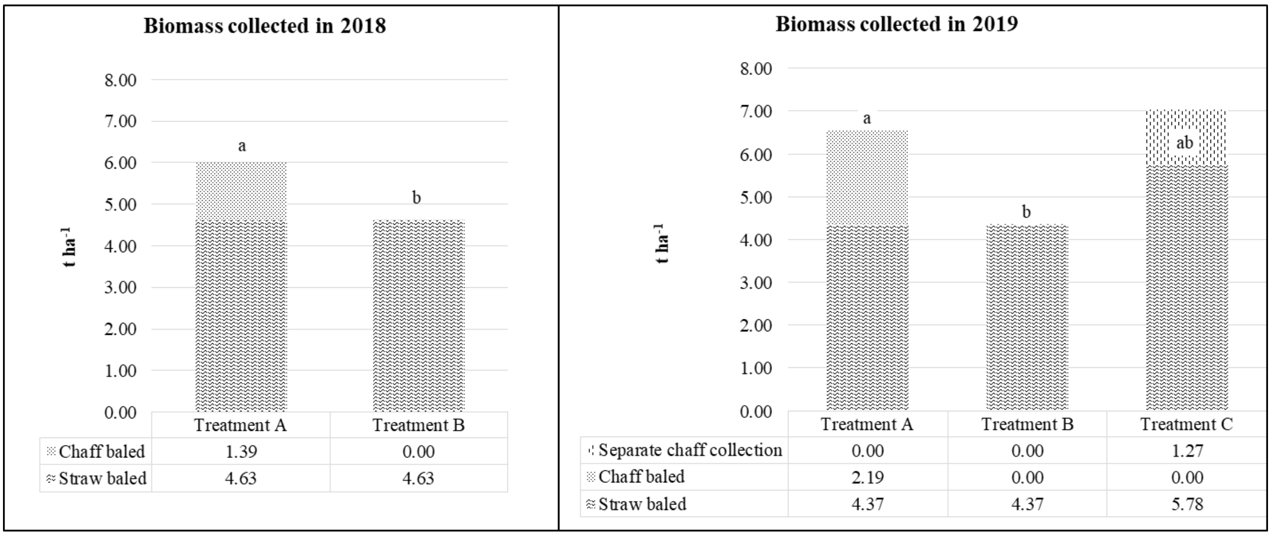


Figure 4. Biomass collected (f.m.) per treatments during the tests carried out in 2018 and 2019. Treatment A: straw and chaff baling; treatment B: only straw baling (chaff spreading on the ground); Treatment C: straw baling and separate chaff collection on trailer.

3.3.2 Bulk density and humidity

The average bulk density of the roto bales (1.8 m in diameter and 1.2 m width) was respectively 111 kg m^{-3} and 131 kg m^{-3} for A mode (straw + chaff) and B mode (only straw) in 2018, while in 2019 was respectively 124 kg m^{-3}, 121 kg m^{-3} and 131 kg m^{-3} for A, B and C mode, with no statistical difference among treatments. The average bulk density of chaff was 62.08 kg m^{-3} (measured only in 2019, treatment C), that is in line with the 56 kg m^{-3} reported by McCartney *et al*. (2006) [8]. The moisture content of different fractions is reported in Table 8.

Table 8. Moisture content in the different fractions of the wheat

	Moisture content (%)	
	2018	2019
Steams	10.5±0.6	11.9±0.8
Stubbles	np	11.1±1.3
Hears	10.0±0.1	10.8±0.5
Chaff	9.3±0.2	9.2±0.9
Seeds	10.3±0.2	9.1±0.1

np: not performed

3.3.3 Biomass losses

Considering the cutting height of 15.7±2 cm (2018) and 12.2±1.5 cm (2019), the stubbles left on the ground accounted for 1.98 ± 0.15 t_{fm} ha^{-1} and 1.71 ± 0.25 t_{fm} ha^{-1}, respectively. Biomass losses are reported in Table 9.

Table 9. Biomass losses (seed, chaff and straw) according treatments in 2018 and 2019

	Seed losses (t_{fm} ha^{-1})		**Chaff losses (t_{fm} ha^{-1})**		**Straw losses (t_{fm} ha^{-1})**	
Treatment	2018	2019	2018	2019	2018	2019
A mode	1.06±0.24	0.04±0.32	0.65±0.59	0.00±0.66	0.78±0.36	2.26±0.22
B mode	1.28±0.06	0.33±0.40	2.04±0.0	2.18±0.0	0.78±0.36	2.25±0.22

C mode	np	0.32±0.10	np	0.90±0.08	np	0.84±0.93

np: not performed

As expected, biomass losses were higher in the case of chaff spreading (treatment "B"), where only 42 % of the theoretical total residues (straw+chaff) were baled in 2019 (49% in 2018). In the case of the discharge of the chaff over the swath (treatment "A"), the total losses accounted only for 38 % in 2019 (36 % in 2018).

By collecting the chaff on trailer separately from the straw (treatment "C"), the total loss of residual biomass was 33 %. In this case only 59 % of the available theoretical chaff was collected (41 % losses). The accurate analysis of the chaff samples revealed that 15.5 ± 0.5 % was made of short straw and no weed seeds were found. The lack of them due to conventional cropping system followed (chemicals are allowed), did not permit the assessment of the weed seeds removal capacity of the Thievin technology.

According to C. Glasner et al., (2019) findings [20] , the percentage of the weed seeds that can be removed by bailing can change over time. In fact, once the chaff is discharged on the swath, after one day, only the 45% of weed seeds remains on top of that, while 35% is found within the swath and the remaining 20% is already lost on the ground. Hence, if the removal of weed seeds is the main purpose of turbine technology application, it is very important to consider both timing and the harvesting chain. The collection of chaff separately from the straw (C Mode) implies higher costs due to the tractor and the trailer involvement that can be only compensated either in the case of organic farming (removing the weed seeds) or in the presence of a dedicated market for chaff (e.g. litter for poultry farming), where the market price of chaff is sufficiently higher than straw.

4. Conclusion

The two years test aimed to assess if significant higher quantity of extra-biomass can be retrieved from the field by including the chaff. Chaff is a considerable portion of the by-products of cereal cropping that is usually left on the ground. The system tested in France permitted to collect the chaff in two different ways: either by direct discharge on the swath or on a trailer towed by a tractor side-by-side the combine harvester.

The potential total biomass assessment in the two years tests resulted slightly different. In 2019 was found higher than 2018 by 1.93 t ha^{-1} while no differences among the ratio between stems, spikes, seed and chaff were found.

Interestingly, in both years, the Thievin did not affect significantly the combine performance. On average the EFC of A and B mode was 2.12 ha h^{-1} that was similar to C mode (2.03 ha h^{-1}). Even the combine fuel consumption (in 2019) was not affected by treatments; the mean value recorder was 46.7 l ha^{-1}.

Differences among the treatments were found during the phase of bailing, particularly in 2019. The EFC was found 11.65 % higher in treatment B respect to treatment A and this is consistent with the total biomass recorded. In fact, it is reasonable to assume that longer time was required for bailing straw and chaff.

In 2019 EFC in treatment C was not statistically different from the others; while fuel consumption was similar to B but lower than A of 57.97 %. Such inconsistency can be attributed to some uninspected losses of chaff occurred during the harvesting manoeuvres that, in fact, increased the total biomass on the swath.

At the end of the experiments, the two-years field trials confirmed the hypothesis that Thievin system can help to increase the total biomass retrievable from wheat cropping. The chaff discharged on the swath and baled with straw was 1.39 t ha^{-1} in 2018 and 2.19 t ha^{-1} in 2019 which account for 30% and 50% respectively as additional biomass. Regarding the possibility to collect the chaff separately, additional treatment in 2019 was introduced which yielded 1.27 t ha^{-1} more biomass, though, it is lower than the amount of chaff collected in A mode.

In conclusion, our findings support the hypothesis that the turbine technology is a valid solution for increasing the total biomass collectable in cereal cropping. However, further economic and technical investigations in different conditions and on different cereal species are strongly encouraged, as well as comparisons with similar technologies available on the market.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Conceptualization and methodology, A.S.; Investigation and data curation A.S., W.S., V.A., S.B.; writing—original draft preparation V.A. and W.S; writing—review and editing, V.A. and W.S.; supervision, L.P. and A.S.; funding acquisition, L.P.

Funding: this research was funded by European Union's Horizon 2020 AGROinLOG project grant number 727961 (http://agroinlog-h2020.eu/en/home/).

Acknowledgments: Authors thank Mr. Robert Bertrand the farm owner and his team for the valid support and assistance provided during the activities, as well as Miss Consuelo Attolico for her indispensable interpretation services.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

7. References

1. Scarlat, N.; Dallemand, J.F.; Monforti-Ferrario, F.; Nita, V. The role of biomass and bioenergy in a future bioeconomy: Policies and facts. Environ. Dev. 2015, 15, 3–34.
2. EU 2015/1513 ILUC Directive. Off. J. Eur. Union 2015, 20–30.
3. European Parliament Report on a 2030 framework for climate and energy policies (20132135(INI)); 2014;
4. Stelte, W.; Sanadi, A.R.; Shang, L.; Holm, J.K.; Ahrenfeldt, J.; Henriksen, U.B. Recent developments in biomass pelletization - a review. BioResources 2012, 7, 4451–4490.
5. Paiano, A.; Lagioia, G. Energy potential from residual biomass towards meeting the EU renewable energy and climate targets. The Italian case. Energy Policy 2016, 91, 161–173.
6. Craessaerts, G.; Saeys, W.; Missotten, B.; De Baerdemaeker, J. Identification of the cleaning process on combine harvesters, Part II: A fuzzy model for prediction of the sieve losses. Biosyst. Eng. 2010.
7. EC Eurostat Database. Eur. Comm. Wheat spelt by area, Prod. humidity 2019.
8. McCartney, D.H.; Block, H.C.; Dubeski, P.L.; Ohama, A.J. Review: The composition and availability of straw and chaff from small grain cereals for beef cattle in western Canada. Can. J. Anim. Sci. 2006, 86, 443–455.
9. Rönnbäck, M.; Lundin, G. Simultaneous Harvesting of Straw and Chaff for Energy Purposes-Influence on Bale Density, Yield, Field Drying Process and Combustion Characteristics. In Proceedings of the XVIIth World Congress of the International Commission of Agricultural and Biosystems Engineering (CIGR) Hosted by the Canadian Society for Bioengineering (CSBE/SCGAB) Québec City, Canada June 13-17, 2010; 2010.
10. Weiß, B.D.; Glasner, C. Evaluation of the process steps of pretreatment, pellet production and combustion for an energetic utilization of wheat chaff. Front. Environ. Sci. 2018.
11. Zhang, H.; Lopez, P.C.; Holland, C.; Lunde, A.; Ambye-Jensen, M.; Felby, C.; Thomsen, S.T. The multi-feedstock biorefinery – Assessing the compatibility of alternative feedstocks in a 2G wheat straw biorefinery process. GCB Bioenergy 2018.
12. Mann, M.E.; Cohen, R.D.H.; Kernan, J.A.; Nicholson, H.H.; Christensen, D.A.; Smart, M.E. The feeding value of ammoniated flax straw, wheat straw and wheat chaff for beef cattle. Anim. Feed Sci. Technol. 1988.

13. Gerling, M.; Dickey, P.C. Patent N 5878696. Absorbant animal bedding 1999, 8.
14. Rush, C.M. Effects of Wheat Chaff and Tillage on Inoculum Density of Pythium ultimum in the Pacific Northwest . Phytopathology 1986, 76, 1330.
15. Shirtliffe, S.J.; Entz, M.H. Chaff collection reduces seed dispersal of wild oat (Avena fatua) by a combine harvester. Weed Sci. 2005, 53, 465–470.
16. Walsh, M.; Newman, P.; Powles, S. Targeting Weed Seeds In-Crop: A New Weed Control Paradigm for Global Agriculture. Weed Technol. 2013.
17. Jacobs, A.; Kingwell, R. The Harrington Seed Destructor: Its role and value in farming systems facing the challenge of herbicide-resistant weeds. Agric. Syst. 2016.
18. Walsh, M.J.; Harrington, R.B.; Powles, S.B. Harrington Seed Destructor: A new nonchemical weed control tool for global grain crops. Crop Sci. 2012.
19. Jakobsen, K.; Jensen, J.A.; Bitarafan, Z.; Andreasen, C. Killing weed seeds with exhaust gas from a combine harvester. Agronomy 2019.
20. Glasner, C.; Vieregge, C.; Robert, J.; Fenselau, J.; Bitarafan, Z.; Andreasen, C. Evaluation of new harvesting methods to reduce weeds on arable fields and collect a new feedstock. Energies 2019, 12.
21. Pari, L.; Alfano, V.; Scarfone, A.; Bergonzoli, S.; Suardi, A.; Lazar, S. Best available technologies to harvest cereal chaff. In Proceedings of the European Biomass Conference and Exhibition Proceedings; 2018.
22. EU Agroinlog - Integrated Biomass Logistic Centres fo the Agro-Industry Available online: http://agroinlog-h2020.eu/en/home/ (accessed on Jan 17, 2020).
23. Thievin Matériel agricole, travaux publics & environnement Available online: https://www.thievin.fr/.
24. ASAE EP496.2 Agricultural Machinery Management. ASAE Stand. 2000, 344–349.
25. ISO 17828:2015 Solid biofuels - Determination of bulk density 2015, 8.
26. EN ISO 18134-2:2017 Solid biofuels - Determination of moisture content - Oven dry method - Part 2: Total moisture - Simplified method (ISO 18134-2:2017) 2017.
27. Unger, J.S.; Glasner, C. Cost analysis of chaff harvesting concepts in Germany. Agronomy 2019.
28. INRA Recuperateur de menues pailles «turbo paille de Thievin»; 2011;
29. CUMA Journée Technique: Récuperation des menues pailles 2015.
30. Thiérart Etude, conception et réalisation de machines spéciales Available online: https://www.thierart.fr/ (accessed on Jan 17, 2020).

MAIZE COB HARVESTING: FIRST ASSESSMENT OF AN INNOVATIVE SYSTEM

L. Pari, S. Bergonzoli*, A. Suardi, V. Alfano, A. Scarfone, S. Lazar
Council for Agricultural Research and Economics, Research Center for Engineering and Agro-Food Processing (CREA-IT)
Via della pascolare, 16. 00015 Monterotondo (Rome) - ITALY
*Corresponding author: Simone Bergonzoli, simone.bergonzoli@crea.gov.it.

ABSTRACT: The maize cob is still an untapped biomass, being rarely used and normally left on the soil. Maize cobs, are considered to have a very limited nutritional value for the soil or as animal food. Therefore, collecting all of it, for energy or bio-based materials pruction, will not have negative impact on the soil neither will affect food security. The objective of the paper was to assess the performances of the innovative Harcob system to collect the maize cob. Different tests were performed during maize grain harvesting in September 2017 using a commercial combine harvester machine equipped with the Harcob system. It was possible to harvest 2 t ha^{-1} of cob, with a material capacity of 4,1 t h^{-1}. The cob losses were lower than 20 %, highlighting the right functioning of the system. Moreover, the unloading operation is performed by an innovative auger system that ensures no blocking problems and requires around 3 minutes, allowing the discharging of maize cob and grain at the same time.

Keywords: agricultural residues, harvesting, maize

1 INTRODUCTION

In the last years, the concept of bio-economy has become a hot topic in Europe and some research programs are focused on unlocking the potential of certain biomass resources that are currently underutilised.

From these un-tapped resources, the maize cobs have risen the interest due to their abundance, low cost and favorable properties [1]. According to EUROSTAT, more than 9 Mha in EU28 are cultivated yearly with grain maize. Considering an average yield of 1 t ha^{-1} of cob this would mean that more than 9 Mt yr^{-1} of maize cob could be available to be collected in Europe [2, 3]. Its interesting properties enable a wide array of applications such as: 1) biomass for energy 2) absorbent for animal bedding or substrate in hydroponic cultivation 3) adsorbent for production of active carbon for water treatment, among other applications 4) abrasive material for metal or wood surface conditioning.

On the other hand, soil fertility decline is currently a key issue in Europe and sometimes faced with the utilisation of agricultural on-field residues. The removal of crop residues should be balanced against the environmental impact (soil erosion), maintenance of nutrients and soil organic matter levels, and preservation of productivity levels [4]. When considering the role of crop residue in the maintenance of soil productivity, maize cob (representing 15-20 % content of maize stover) collection offers advantages when compared to the harvesting of the whole stover. Cobs have lower concentrations of several nutrients (N, P, K, S, and Ca) compared to stover fractions.

Turning cobs into a valuable and cost-effective feedstock greatly depends on the harvest technology. Currently, the maize cobs are rarely used, being normally left on the soil uncollected or collected with the stover [5]. One-pass harvest equipment that can collect maize grain as well as cobs should be developed [6].

Three harvesting methods enabling cob collection are currently in use, but the challenge is still to separate cobs from grain (and potentially from the stover) without slowing down the harvest operation.

One-pass cob collection requires less equipment, labour and passes over the field than other methods, and even less if no wagon is required. Advantages are also present in the fact that the maize cobs are collected directly out of the combine and the feedstock produced is free from contaminants such as sand or stones, which could present challenges for bioenergy production [7].

An Italian company has designed a system to be applied in some commercial harvesters available in the market. The system consists of a device to separate maize cob from the other residues (leaves, stem, culm, etc.) and collect it in an additional tank (9 m^3).

During the European project called BeCool, machineries to harvest cereal residues were investigated in order to set up and optimize mechanical solutions to increase the efficiency of recovering of agricultural residues.

The purpose of the tests showed in this paper was to determine the operating parameters of the machine and the quality and effectiveness of its work in order to assess the performances of the innovative harvesting system (Harcob) to collect the maize cob.

2 MATERIALS AND METHODS

2.1 Field and equipment characteristics

The study was conducted in September 2017 within “Giletta” farm, placed in the Northern Italy at Revello (44.709920 N and 7.435711 E), Cuneo province. The farm is oriented to dairy farming and has a biogas power plant of 250 kWe fed by cow manure as well as litter and maize residues (cob and stalks). The harvesting tests were performed in three different maize fields (A, B and C) of about 2 ha each. The fields were sown with maize in April 2017. The test was performed during maize grain harvesting carried out with a combine harvester machine, model Axial Flow 7140, equipped with the system to harvest maize cob. The Italian company Racca has designed and patented a system to be applied in some commercial harvester.

As mentioned previously, the system is able to separate maize cob from the other residues (leaves, stem, culm, etc.) and collect it in an additional tank (9 m^3). Depending on the final use of the product, the system is able to control the amount of these other residues collected. The cob is stored till is unloaded with an innovative auger system ensuring no blocking problems. The unloading requires around 3 minutes, allowing the discharging of maize cob and grain at the same time. Regarding the extra consumption linked to the recovery of cobs, according to the manufacturer, the combined harvesting can mean a surplus of 5 % in the power required by the machine in comparison to normal operation. The combine can still be used under normal conditions, by manually disconnecting the main drive belt.

The adaptation can be mounted only on some of the self-propelled Axial Flow harvester models: 6088-7088, 6130-7130 and 6140-7140.

Figure 1. View of the Harcob system

2.2 Pre-harvesting

In order to study the crop characteristics, before starting the work, ten sampling plots (replicates) of 1 m^2 were randomly selected inside each experimental field. All plants of each plot were hand-harvested by cutting at ground level and the following biometric and productive characteristics registered: number of the plants, stem diameter at ground level, plant height and aboveground biomass yield of each plot. All the ears of each plot were weighted separately in order to study the biomass fractions of the maize crop and the ratio between ears and the total biomass. Four samples of maize cobs, of maize seeds and of leaf biomass were randomly collected in each experimental field, weighed and stored into vacuum-packs to measure the moisture content. The moisture content (MC %, w-% ar) of the different biomass was determined according to ISO 14774-2:2009 [8]. Bulk density (kg/m^3) of the maize cob was assessed taking 10 samples of cob randomly selected from the biomass discharged by the machine and was measured according to ISO 17828:2015 [9].

2.3 Work time study

The study of the machine performance was carried out during maize grain and cob harvesting. All the operations were analyzed following the CIOSTA (Comité International d'Organisation Scientifique du Travail en Agriculture) methodology and the recommendations from the Italian Society of Agricultural Engineering (A.I.I.A.) 3A R1. A reference to these methods can be found in [10]. Operation time, distance harvested, surface of each experimental field and weight of products collected were measured during the harvesting operation in order to assess the following working parameters: field efficiency (FE %), operating speed (m s^{-1}), effective field capacity (FC, ha h^{-1}), productivity (P, t h^{-1}) and yield (Y, t ha^{-1}).

The main working times were:

TO = total operating time (%)

TE = effective operating time (%)

TA = accessory time (% of operating time, TO)

TE was derived from

TE = TO-TA

The accessory time included the time for turning and maneuvering. No rests or delays occurred.

Maize grain and cobs per each block, the trailers with seeds and cobs were weighed separately in the farm scale.

2.4 Post-harvesting

The cob losses were estimated by gathering and weighting the material not harvested during passage of the machine, and any cob left on the ground. Five random plot of 10 m^2 were chosen per each experimental field, the cob present in each plot was collected and weighted.

Percentage of losses (L %) were then estimated as the ratio of cob losses to the sum of cob yield and cob losses, for each experimental field. The sum of net yield and cob losses represented the total yield potential (Y, t ha^{-1}).

3 RESULTS AND DISCUSSION

Results of pre-harvesting sampling are described in Table I. The values are related to the average of ten replicates of sampling plot (1 m^2) per each field, mean values are related to the mean of the three fields. The average value of the stem diameter was 2,3 cm with a maximum value of 3,3 cm. The plant height showed a great variability ranging between 155 and 420 cm with an average value of 325,8 cm. The average weight of the total biomass was 50,7 t ha^{-1}, showing a great variability ranging between 42,8 to 55,1 t ha^{-1}. The ears weight was 19,5 t ha^{-1} in the average with 17,0 and 20,9 t ha^{-1} of minimum and maximum values respectively. The average value of the ears/biomass ratio was 44,0 %.

Table I. Main crop characteristics of the experimental fields

	Stem diameter (cm)	Plant height (cm)	Total biomass (t ha^{-1})	Ears weight (t ha^{-1})	Ratio ears/biomass (%)
A	2,2±0,4	290,7±34,4	42,8±10,9	17,0±8,1	41,8
B	2,5±0,4	332,6±20,2	52,3±6,1	20,9±7,3	44,2
C	2,3±0,7	352,3±42,1	55,1±10,8	20,6±7,8	41,8
Mean	2,3±1,5	325,8±31,9	50,7±6,4	19,5±2,2	44,0

The results of the work time study are reported in table II. The average value of effective field capacity was 2,1 ha h^{-1}, values recorded in the replicates ranged between 1,7 and 2,1 ha h^{-1} showing low variability. The average value of grain and cob yield was 13,6 and 2 t ha^{-1}, respectively. The cob losses were lower than 20 % with values ranging between 14 and 18 % and an average value of 16,7 %. In the field C lowest values of Effective field capacity (1,7 ha h^{-1}) and Material capacity of grain and cob (23,0 and 3,1 t h^{-1}, respectively) were recorded. This fact could be ascribed to the highest amount of total biomass registered in the same field (5,5 kg) that caused the forward speed reduction of the harvesting machine.

Table II. Performance test, results of the combine harvesting machine

	FE (%)	FC (ha h^{-1})	Grain P (t h^{-1})	Grain Y (t ha^{-1})	Cob P (t h^{-1})	Cob Y (t ha^{-1})	Cob L (%)
A	65,6	2,2	31,4	14,1	4,7	2,1	18
B	67,8	2,2	29,4	13,2	4,6	2,1	18
C	65,7	1,7	23,0	13,5	3,1	1,8	14
Mean	66,4 ±1,2	2,1± 0,3	27,9 ±4,4	13,6 ±0,5	4,1± 0,9	2±0,2	16,7 ±2,3

The average value of the leaf moisture content was 68,93 %, with values ranging between 68,3 and 70,0 %. Values of moisture content of grain showed a great variability with maximum value of 28,1 % and minimum value of 19,6 %, a great variability was also highlighted in cob moisture content where values ranged between 37,2 and 56,6 % and an average value of 49,10 %. The field C recorded lowest values of grain and cob moisture content, 24,57 and 49,10 %, respectively.
The average bulk density resulted in 316,6 kg m^{-3}.

Table III. Means (±SD) of moisture content and bulk density of the biomass

	Leaf MC (%)	Grain MC (%)	Cob MC (%)	Bulk density (kg m^{-3})
A	70,0±1,1	26,0±2,3	53,5±3,1	316,6±44,6
B	68,3±2,7	28,1±3,5	56,6±5,8	
C	68,5±2,1	19,6±1,0	37,2±2,7	
Mean	68,93±0,92	24,57±4,42	49,10±10,42	

4 CONCLUSIONS

The amount of the biomass per hectare was in the average 50,7 t, being the amount of ear 19,5 t and the ear/biomass ratio 44 %. Considering this amount of biomass, using this combine harvester machine equipped with the Harcob system, it was possible to harvest 2 t ha^{-1} in the average of cob, with a material capacity of 4,1 t h^{-1}. The challenge remains the need of lowering the value of cob losses that were 16,7 % in the average.

Because of its high moisture content after harvesting (49,1 % on average), the maize cob can be considered an appropriate biomass to be fed directly into a biogas power plant. In the case of a scope for animal bedding, natural drying could be a cost-effective option to reach lower moisture contents. Instead, it needs to by dried with a forced system if it must be used for animal feed production.

The proper functioning of the Harcob system and the quantity and quality of the maize cob, also considering the availability of this product in EU, makes this untapped material an attractive biomass resource that can be used for many purposes.

6 REFERENCES

[1] Jansen C, Lübberstedt T (2011) Turning maize cobs into a valuable feedstock. Bioenerg Res. doi: 10.1007/s12155-011-9158-y

[2] Pollex, A. and T. Zeng. Initiators Handbook MIXBIOPELLS, 2012.

[3] Khawaja, C., Janssen, C., 2015. D4.3a of the SUCELLOG project - Summary of the current situation of Tschiggerl Agrar GmbH and feasibility study. SUCELLOG project, Triggering the creation of biomass logistic centres by the agro-industry

[4] Wilhelm, W.W., Johnson, J.M.F., Hatfield, J.L., Voorhees, W.B., Linden, D.R.. 2004. Crop and Soil Productivity Response to Corn Residue Removal: A Literature Review. Agronomy Journal. Agron. J. (96):1-17

[5] Shinners KJ, Binversie BN, Muck RE, Weimer PJ (2007). Comparison of wet and dry corn stover harvest and storage. Biomass Bioe 31:211–221.

[6] Johnson JM, Wilhelm WW, Karlen DL, Archer DW, Wienhold BJ, Lightle DT, Laird DA, Baker JM, Ochsner TE, Novak JM, Halvorson AD, Arriaga FJ, Barbour NW (2010) Nutrient removal as a function of corn stover cutting height and cob harvest. BioEnergy Res 3:342–352.

[7] Zych, D. 2008. The viability of corn cobs as a bioenergy feedstock. West Central Research and Outreach Centre, Morris, MN. Univ. of Minnesota, Minneapolis. p. 1–25

[8] ISO 14774-2:2009, Solid biofuels – Methods for the determination of moisture content – oven dry method

[9] ISO 17828:2015, Solid biofuels - Determination of bulk density, (2015) 8.

[10] Bodria, L., Pellizzi, G., Piccarolo, P., 2006. Meccanica agraria vol. II: la meccanizzazione. Il Sole24Ore, Bologna, Italy.

8 ACKNOWLEDGEMENTS

The works were performed in the framework of the European project "BeCool" (grant agreement No. 744821). The BeCool project is financed by the EU H2020 programme.

The authors wish to thank Mr Gabriele Racca, and the employees of Giletta farm for for the authorization to conduct the tests and for their assistance in performing them and their professionality and availability.

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Article

Economic Distance to Gather Agricultural Residues from the Field to the Integrated Biomass Logistic Centre: A Spanish Case-Study

Alessandro Suardi [1], Simone Bergonzoli [2,*], Vincenzo Alfano [1], Antonio Scarfone [1] and Luigi Pari [1]

[1] Council for Agricultural Research and Economics, Research Center for Engineering and Agro-Food Processing (CREA-IT), Via della Pascolare, 16, 00015 Monterotondo, Italy

[2] Council for Agricultural Research and Economics, Research Center for Engineering and Agro-Food Processing (CREA-IT), Via Milano, 43, 24047 Treviglio, Italy

* Correspondence: simone.bergonzoli@crea.gov.it

Received: 12 July 2019; Accepted: 7 August 2019; Published: 10 August 2019

Abstract: A big amount of agricultural residues are generated from crop production and partially remain in the field after harvest. Removing the excess of residues after crop harvesting can increase farmer income, providing feedstock that could be used for industrial and energy purposes. The costs for collection and transport of straw and stalks are site- and region-specific and depend on the availability of agricultural residue and on how much of the residue is removed from any specific field or location. If the biomass is baled then it is required to upload the bales on a trailer, transport and unload all the baled biomass to the storage center. On the other hand, if a self-loading wagon is used the loose biomass collected, it must be unloaded every time the wagon is completely full. The distance and the harvesting system used influence the costs and should be analytically studied to avoid turning a possible profit into a disadvantageous business. The research represents a real case study to evaluate, which is the maximum distance to the biomass logistic center from which it is more economically convenient to gather the wheat and corn residues in bales instead of using a self-loading wagon. The results show a lower harvesting unitary cost for the self-loading forage wagon respect to the baling system. Although the study showed delivery distances over 11.4 km for wheat straw and 16.0 km for maize stalks, the use of the self-loading forage wagon is no longer convenient, and baling is the preferred harvesting system.

Keywords: agricultural residue; maize stalk; cereal straw; harvesting; baler; self-loading wagon; cost analysis; transport cost

1. Introduction

The European Union Directive on the promotion of the use of energy from renewable sources

(RED) includes a binding target of a 20% share of renewable energy in energy consumption in EU by 2020 [1,2]. Bioenergy sector, as possible solution to this issue, has attracted much attention in last years because feedstocks can be suitable surrogates for traditional energy production systems which are finite, non-renewable, and cause of environmental concerns [3]. It is now foreseen that biomass could provide around two-thirds of the renewable energy share in 2020 according to scenarios. The bioenergy value chain requires the delivery of the biomass feedstock from the production sites to the utilization centers. Along this path, the biomass passes through facilities and processes that composed the so-called biomass supply chain. Each step of the supply chain needs specific expertise, technology, and operations including biomass production, feedstock transportation, processing, and

Energies **2019**, *12*, 3086; doi:10.3390/en12163086 www.mdpi.com/journal/energies

consumption. The design of the supply chain is a fundamental aspect for the improvement of its performance and efficiency [4].

Excluding the forestry sector, agriculture can be a source of biomass for energy purpose either by establishing plantations of bioenergy crops (e.g., rotation forestry, perennial, or annual herbaceous crops) or by removing residue from cropland. Crop residue is defined as the non-edible plant part that is not harvested and left in the soil [5]. The different residues produced by the agricultural sector may contribute to reach the goal defined by renewable energy directives since a big amount of agricultural byproducts are generated from crop production and still remain in the soil after harvesting [6]. While production of energy from crop by product is already a possible initiative, the potential risk of crop residue removal on soil organic carbon (SOC) and soil organic matter (SOM) deserves attention. Studies have highlighted that SOM content is directly related to the amount of residue maintained on the soil [7]. Furthermore, crop residues remaining on the fields are not a waste but provide numerous ecosystem services including SOC sequestration, being a direct source of SOC pool [8]. The availability of crop byproducts is then related to the quantity that can be removed from the soil to maintain its fertility and to other uses as those related to industrial and agricultural sectors. Crop byproducts defend land from erosion, sustain or increase soil organic matter, preserve macro- and micronutrients of the soil, while also supporting water retention capacity [9]. A proper degree of residue removal should be identified on the basis of the quantity that must be maintained in the field to keep soil fertility and avoiding soil impoverishment and erosion [10,11].

The consequences of residue removal rely on the crop, farm management (crop cycle, soil operations, fertilization), site characteristics (e.g., soil type and fertility, soil organic matter, water content, topography and slope, etc.), climate conditions (e.g., wind, precipitation) and harvesting system [12].

The cost of the logistic operations is another aspect that should be taken into consideration when a new agricultural waste for energy value chain is implemented. In fact, it represents one crucial bottleneck in developing the supply chain for biomass feedstock utilization for energy production.

The increasing feedstock request and the sophisticated supply chain highlight the importance of a global management of the biomass procurement system.

Each feedstock supply chain needs different biomass characteristics on the basis of energy requirements trends, energy processing system, use of the energy produced, and the type of the logistic chain [13]. Therefore, the financial barriers as biomass collection, transportation, and processing heavily affect the economic feasibility of crop byproduct utilization [14,15].

One of the most interesting energy feedstocks is stalk, due to its cellulose richness and spread cultivation [16]. Cereal stalk is the non-grain part of the plant (e.g., corn or wheat) that is not collected and remains on the soil, except stubble, husk, leaves, cobs or chaff.

Furthermore, in the EU the main conventional uses of cereal straw (mainly wheat straw) within the agriculture sector are animal feed integration, livestock litter, soil improver, frost prevention for some horticultural product and compost production. Outside the agricultural sector cereal straw is used for thatching, as traditional building materials (fiber boards, insulation material), and for energy (heat, power, fuels) [17].

Instead, corn stalks are usually used for low-value applications like animal feeding and bedding; however, as reported by Kadam (2003), it can also be used for the production of composite product (e.g., particleboard), pulp and paper, or for energy production, either through direct combustion of residues or through microbial conversion of residues to ethanol fuel [18]. Removing the excess amount of residues can reduce the need to till, increase farmer income providing millions of dry tons of feedstock for the production of fuels, chemicals, and materials. However, the assessment of the economic sustainability of the field and transport phases is critical to decide the final use of the biomass and the best harvesting technique to be used for each specific case. The harvesting of cereal residues is normally carried out by using the haymaking equipment

(i.e., rake, baler, etc.), but no attention is often paid on the selection of the machines that better fit to the agricultural residues logistic chain or that could reduce the harvesting costs. In fact, sometimes, equipment already available in the farm that is not acquired for the collection of the residues could be used also for this purpose reducing their harvesting costs.

During the European project AGROinLOG [19], the concept of Integrated Biomass Logistic Centre (IBLC) was defined as a "business strategy for agro-industries to take advantage of unexploited synergies in terms of facilities, equipment, and staff capabilities to diversify regular activity both on the input (food and biomass feedstock) and output side (food, biocommodities and intermediate biobased feedstock) thereby enhancing the strength of agro-industries and increasing the added value delivered by those company". In the same project, an important agro-industry of fodder located near Zaragoza (Spain) was chosen as a case study to demonstrate the possible integration of an agricultural residue supply chain to the standard activity carried out by the company. In this particular study, the agricultural equipment usually used for the harvesting of alfa-alfa (Medicago sativa, L.) was used also for the collection of the cereal straw and maize stalks in order to assess the economic feasibility of the harvesting and transportation of biomass from the field to the IBLC.

The costs for collection and transport of straw and stalks are site- and region-specific and depend on the availability of agricultural residue (tons of residue per hectare of land—Mg ha^{-1}) and the amount of the residue that is removed from any specific field or location. If the biomass is baled, then it is required to upload the bales on the trailer and transport and discharge all the baled biomass to the storage center. On the other hand, if a self-loading trailer is used, the loose biomass collected must be discharged every time when the wagon is completely full. The distance from the field to the IBLC where the biomass is stored affects the cost of transportation and should influence the choice of the equipment used.

The objective of this study was to evaluate the performance and to estimate the costs of two different harvesting systems and supplying for wheat straw and corn stalks, in order to define the best method to gather and transport the residual biomass from the field to the storage center according to the distance.

2. Materials and Methods

2.1. Agroindustrial Pascual Sanz SL (APS): Case Study

The large field tests have been carried out near Agroindustrial Pascual Sanz SL (APS) headquarter (Zaragoza, Spain—41°38^{0}23.4” N 0°45^{0}6.2” W). The company is dedicated to the production of dehydrated forage in bales or pellet format. The raw material is mainly alfalfa and is purchased in the market from regular traders in bale format (around 10% of the alfalfa purchased), and from alfalfa farmers through harvesting service; their purchased product is brought to the agro-industry shredded in regular alfalfa trailers (around 90% of the raw material—100 farmers).

In minor occasions and depending on quality demand of the consumer, they purchase other forage products (like Sudangrass) to be mixed with the alfalfa. Around 50,000 Mg of alfalfa is received from April to November, which is the working season of the plant to make bales (the 85% of the production) and pellets (the 15% of the production) for the animal feed market. Transport to consumers is normally arranged by the agro-industry with external companies. The new business line has been conceived to take advantage of the idle period of the equipment in the plant from December to March. During this time, new pellets for two different purposes will be produced: Energy use and bio-composite materials. A production of 6000 Mg y^{-1} has been considered as the optimal for the company as a first approach, although the maximum capacity is around 10,000 Mg y^{-1}. The raw material for the production of pellets will be cereal straw, maize stalks, and Sudan grass to be purchased to the farmers around. In order to upgrade the quality of the pellet when the goal is to satisfy the energy demands, woodchips will be acquired. The current line is able to process any type of herbaceous products and woodchips with minor modifications of the operation mode or increasing the maintenance, although the capacity of the line will decrease. During the project AGROinLOG, the plant flexibility will be increased by enabling the production of new pellets during the current season of inactivity (December to March)

with a negligible investment. Furthermore, two additional markets will be tackled with these new products: Bioenergy and bio-composites.

2.2. Equipment Description

The tests were performed in Zaragoza (Spain) in July 2017 for the wheat straw harvesting, and in October 2017 for the maize stalks harvesting. During each trial, two harvesting systems were tested and compared, the baling and the self-loading wagon systems (Figure 1). The machines used during the tests are common tractors and equipment used by APS company to harvest alfalfa.

The baling system (HS-A) was composed by a square baler New Holland BB940 (SB) towed by a tractor New Holland T6050 (TR1). With a second tractor John Deere 6420 (TR2) the bales were

loaded on a trailer (TL), and a third tractor John Deere 6420 (TR3) was used to transport and download the bales at the storage center.
The self-loading system (HS-B) was composed by a self-loading wagon (SLW) Lacasta mod. Elefant P31L towed by a second tractor New Holland T6050 (TR4). This system was used for both harvesting and transport the products to the storage center. A common protocol was used during tests to collect the primary data for the study.

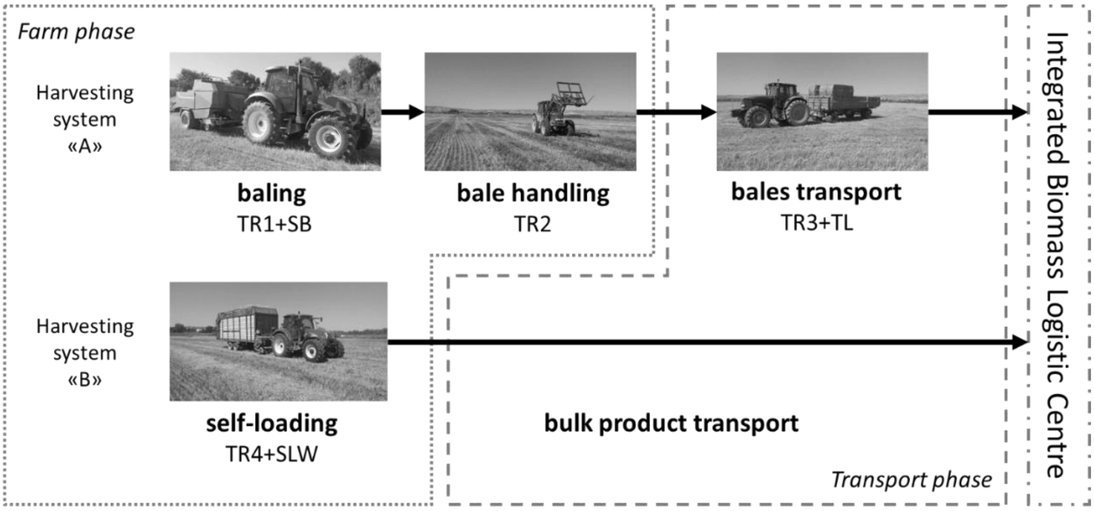

Figure 1. Scheme of the harvesting systems compared during the tests.

2.3. Dataset and Statistical Analysis

A split plot experimental design was used for each harvesting test. The fields were divided in three blocks (statistical replications) for each treatment (baling and self-loading tests). The performance analysis was carried out using primary data collected during the tests: These were the working times of the machines used, the bulk densities of the product transported, fuel consumption of the tractors, biomass losses during the harvesting stage and the moisture of the biomass at the IBLC. The secondary data collected were all the economic parameters necessary to carry out the cost analysis of both logistic chains. The cost investments (€), service life (y), resale percentages (%), annual usages (h y^{-1}), interest rate (%), the repair factors (%) and insurance (%) of the machines, as well as the labor costs were obtained by personal communication and from literature (Table 1). After verifying the normality of the distributions, the data statistical significance were analyzed by ANOVA test [20]. Furthermore, the post-hoc Tukey test ($p < 0.05$) was used to find means that were significantly different from each other.

2.3.1. Harvesting Data

Plots with similar area were defined and measured before each harvesting stage. The study of the machine performance was carried out for both the two different machinery chains for each residue collected. The work time study was performed according to the CIOSTA (Comité International d'Organisation Scientifique du Travail en Agriculture) methodology and the recommendations from the Italian Society of Agricultural Engineering (A.I.I.A.) 3A R1 [21,22].

Operation time, harvested area, and wheat residues collected per each experimental field were measured during the harvesting tests in order to calculate the following working parameters: Field efficiency (%), operating speed (m s^{-1}), effective field capacity (ha h^{-1}), material capacity (Mg h^{-1}), and yield (Mg ha^{-1}).

Furthermore, fuel consumption was determined through machine tank refilling until full level at the end of each experimental unit (block) using a graduated large cylinder to define the volume of fuel consumed (l ha^{-1} or l Mg^{-1} of biomass harvested). Each block was started with the tank completely full. The fuel consumed was proportioned to the exact surface of the block tested to define the fuel consumed per hectare in that experimental unit. The fuel consumption was determined in each block to evaluate if there are statistically significant differences in the consumption (and consequently in operative costs) of one system with respect to the other.
It is important to highlight that, even if the refill method, to measure the fuel consumption is very common and has the advantage of being very easy to apply in the field, and sometimes it is the only method that can be used; its accuracy has been questioned in many studies, especially when the amounts to be measured are minute, and the measurement error is difficult to assess [22].

Working-time study and fuel consumption measurement were performed for all the steps involved: Harvesting, transport, and biomass discharging at the IBLC.

For the treatment "A" the parameters were measured, according to the above described methodology, also for the operations of uploading of the bales on the trailer.

2.3.2. Post-Harvesting Data

The biomass losses were estimated by gathering and weighting the material that was not harvested by the equipment but left on the ground. Three random plots of 10 m^2 were chosen per each block, and the biomass present in each plot was collected and weighted with a portable scale. Percentage of losses (%) were then estimated as the ratio of residue losses (Mg ha^{-1}) to the sum of biomass yield (Mg ha^{-1}) and residue losses (Mg ha^{-1}) for each block. The sum of net biomass yield and biomass losses represented the total biomass yield potential (Mg ha^{-1}).
Furthermore, three samples of cereal residues were randomly collected, weighed to determine the moisture content (%). The moisture content (MC) of the biomass was determined according to 18134-2:2017 [23]. The bulk density (kg m^{-3}) of the loose biomass was assessed taking 3 samples of biomass for each block, harvested by the self-loading trailer, randomly selected from the biomass discharged by the machine and was measured according to ISO 17828:2015 [24]. The bulk density (kg m^{-3}) of the baled biomass was measured after weighting and calculating the volume of three bales randomly chosen from each block.

2.3.3. Cost Analysis

The economic analysis was focused on both ownership and operating costs, according to the parameters measured during the field tests (primary data) or by using standard values provided by the CRPA methodology [25]. Interviews with agroindustry owners and with their usual suppliers have provided further costs items and have validated the data measured during the field tests.

The hourly costs for all the tractors and equipment tested during the harvesting, loading, unloading and transport, were calculated for both logistic chains (baling and self-loading) according to [25,26] (Table 1).

For the HS-A, the hourly costs (H_c) for transport, the mean load capacity (L_c), and the mean transport speed (V) were used to calculate the unitary cost (T_c) per tons of biomass transported per km (€ km^{-1} Mg^{-1}). L_c, and V were evaluated as the average of three measurements of the transport from the field to the storage center and return (T_d).

Table 1. Base-case parameters used for the economic analysis of the harvesting and transport of maize stalks and cereal straw using both baling harvesting system (HS-A) and self-loading harvesting system (HS-B).

	HS-A					HS-B	
	TR1	**SB**	**TR2**	**TR3**	**TL**	**TR4**	**SLW**
Equipment Type	Tractor New Holland T6050	Baler New Holland BB940	Tractor John Deere 6420	Tractor John Deere 6420	Trailer	Tractor New Holland T6050	Lacasta Elefant P31L
Investment (k€) *	77	75	72		10	77	73
Service life (years) *	10	10	10		20	10	10
Remaining value (%) *	35	35	35		10	35	25
Annual usage (h y^{-1}) *	800	250	800		-	1200	1000
Interest rate (%) §	4	4	4	4	4	4	4
Insurance (€ y^{-1}) *	200	120	180		25	200	120
Workers (n) **	1	-	1	1	-	1	-
Labor cost (€ h^{-1}) *	11	11	11	11	11	11	11
Repair and Maintenance costs (€ h^{-1}) **	5	13	5	5	1	4	8
Fuel consumption for straw supply chain (€ h^{-1}) **	7.93	-	4.67	9.54	-	Harvest. 12.13 Transp. 11.80	-
Oil consumption for straw supply chain (€ h^{-1}) **	0.24	-	0.22	0.22	-	0.24	-
Fuel consumption for stalk supply chain (€ h^{-1}) **	8.29	-	7.48	7.07	-	Harvest. 8.68 Transp. 10.85	-
Oil consumption for stalk supply chain (€ h^{-1}) **	0.24	-	0.22	-	-	0.24	-

* Personal communication by the Director of Agroindustrial Pascual Sanz SL (Zaragoza, Spain); ** Self-elaboration by primary data. § (Assirelli and Pignedoli, 2005).

The unitary costs per tons (€ Mg^{-1}) of biomass transported per km for the HS-A (baled biomass) was calculated according to the following formula:

$$T_{ca} = \frac{H_c}{V} \times L_c \qquad (1)$$

where:

T_{ca} = Unitary transport costs (€ Mg^{-1} km^{-1}) for the harvesting system "A";

H_c = Transport hourly cost (€ h^{-1}); V

= Mean transport velocity (km h^{-1});

L_c = Mean load capacity (Mg).

Unlike for the baling system, the self-loading wagon must unload the biomass every time that is completely full. According to ASAE methodology [26] the transport timing to unload the residue to the storage center represents time lost for harvested material handling, and it is unproductive time. Since, the transport timing for the HS-B increases proportionally to the distance that there is between the field to the storage center, it negatively influences the effective field capacity (ha h^{-1}) of the harvesting system. Therefore, the calculation of the unitary transport cost for the HS-B was made by separating the time lost for transporting the biomass to the storage center from the time used for calculating the effective field capacity of the system, according to the following formula:

$$T_{cb} = H_c \times \frac{h_t}{S} \times B_h \quad (2)$$

where:

T_{cb} = Unitary transport cost (€ Mg^{-1} km^{-1}) for the harvesting system "B";

H_c = Transport hourly cost (€ h^{-1});

h_t = Transport timing (h km^{-1}); S = Harvested area (ha);

B_h = Biomass harvested per hectare (Mg ha^{-1}).

The stalks and the straw were gathered to the same storage center located at Agroindustrial Pascual Sanz SL headquarter.

The maximum distance between the fields and the storage center from which it is more economically convenient to gather the biomass with balers instead of forage hauling equipment (self-loading wagon)
was obtained calculating the system equations $y_a = f(x)$ and $y_b = f(x)$ for the HS-A and HS-B per residue type (straws and stalks). The dependent value "y" is the harvesting and transport costs (€ Mg^{-1}), while the "x" value represents the distance from the field to the storage centre (km).

3. Results and Discussion

3.1. Performance of Harvesting Systems

There were large variations in results of machine performance of the two harvesting systems, depicted in Figure 1, when different biomasses were harvested. This was certainly influenced by the different amount of residual biomass available in maize and wheat. For both maize stalks harvesting systems tested, lower operating speed and, consequently, lower field capacity were observed compared to the results obtained during the harvesting of cereal straw. However, the amount of maize stalks collectable was higher as well as the material capacities (Table 2).

Table 2. Machine performance and quality of the work of the harvesting phase.

Biomass Type	Maize Stalk	Wheat Straw

Harvesting System	HS-A	HS-B	$p < 0.05$	HS-A	HS-B	$p < 0.05$
Equipment type	SB	SLW		SB	SLW	
Operating speed ($m\ s^{-1}$)	1.28 ± 0.06	0.95 ± 0.14	*	2.19 ± 0.18	1.97 ± 0.04	
Field efficiency (%)	85.9 ± 2.9	83.5 ± 1.7		90.2 ± 0.4	89.7 ± 1.3	
Effective Field capacity ($ha\ h^{-1}$)	2.27 ± 0.23	1.31 ± 0.22	*	4.67 ± 0.23	4.65 ± 0.68	
Material capacity ($Mg_{fm}\ h^{-1}$)	15.86 ± 4.70	10.81 ± 0.49	*	11.18 ± 1.15	10.76 ± 1.75	
Biomass yield ($Mg_{fm}\ ha^{-1}$)	6.9 ± 1.32	7.4 ± 1.19		2.39 ± 0.20	2.32 ± 0.07	
Bulk density ($kg\ m^{-3}$)	151.36 ± 5.53	89.33 ± 2.31	*	145.75 ± 6.63	18.56 ± 6.46	*
Losses (%)	12.68 ± 4.30	14.68 ± 4.68		1.19 ± 0.42	0.88 ± 0.18	
Moisture content (w_{wb}/w_{wb} %)	13.33 ± 0.58	9.39 ± 0.92	*	6.76 ± 1.87	4.17 ± 0.52	*

* Values marked with asterisks are significantly different ($p < 0.05$) (per parameter and residue type).

Considering maize stalks harvesting, the baling system showed higher values for all the parameters except for biomass yield and losses, while regarding wheat straw harvesting, the baler showed higher results for all the parameters compared the SLW. Statistically significant differences were found for the field capacity and material capacity of the two harvesting systems tested in maize stalks collection, while no differences were found between the same parameters for wheat straw harvesting. No statistically significant differences were observed between field efficiency, biomass yield, and losses for the two harvesting systems in both maize stalks and cereal straw. This result is important for an IBLC because both the harvesting systems permit collecting a similar amount of biomass (similar yield amount per residue type) with similar harvesting losses, not representing discriminative parameters in the decision process for the more adapt collection system. Values of moisture content showed differences statistically significant for each cereal residue as well as for bulk density and operating speed. Results highlighted that the bulk density of the baled biomass was 41.0 and 87.3% higher of the loosed biomass, for stalk and straw respectively. The bulk density of the maize stalk was 79.2% higher than for wheat straw. These values have a great influence on the transportation to the storage center.

Corn residue is usually harvested with balers (large round bales, large square bales, or small square bales) [27]. However, self-loading wagons do not need transport trucks, and they rely on tractor power to harvest and transport. Therefore, self-loading wagons may be a viable method to reduce biomass harvest fuel and labor costs where transport distance is short [28]. Lizotte (2011, 2013) carried out corn stover harvesting tests using self-loading wagon and round baler (RB) collecting 1.44 $Mg_{dm}\ ha^{-1}$ (1.57 $Mg_{fm}\ ha^{-1}$; moisture content of 8%) and 1.85 $Mg_{dm}\ ha^{-1}$ (1.98 $Mg_{fm}\ ha^{-1}$; moisture content of 6.8%) with a RB and a SLW, respectively. The lowest biomass available in the experimental field of Lizotte (2011, 2013) permitted to work faster than the equipment used during our tests, so the field capacity of the round baler resulted 3.8 $ha\ h^{-1}$ going at a work speed of 5 $km\ h^{-1}$ [29,30]. Similarly, our results showed a field capacity of the SLW variable due to the travel distance from the field to the IBLC. Lizotte and Savoie (2013) observed that SLW allowed high field speed that resulted in 10.9 $km\ h^{-1}$ [30].

In our test, the maximum field speed achieved by the SLW was 3.94 $km\ h^{-1}$.

It is clear how the amount of biomass available influences the work speed and so the field capacity of the equipment. In fact, the field capacities of SLW and SB when wheat straw is collected resulted double compared with maize stalk collection due to the smaller quantity of residues to be processed by the machines.

Wheat straw is usually collected by balers, but according to Brownell (2012) the self-loading wagon uses considerably less energy and labor than the traditional forage harvesting system [28].

It should be highlighted that while the baler can harvest the biomass independently from the bale-handling operation that can be performed by another tractor with fork, the self-loading wagon must discharge the biomass to the IBLC or an intermedium storage area every time that the wagon is completely full. Therefore, considering the time required to transport and discharge the biomass, the field capacity of the self-loading wagon decreases as the distance from the field to the storage area increases (Figure 2). This aspect has an important influence on the selection of harvesting system.

As it is possible to see from Figure 2, in the case of straw harvesting by system "B", in the first 5 km of distance between field and IBLC, the field capacity of the SLW passed from 4.05 ha h^{-1} (biomass unloaded directly in the field) to 2.05 ha h^{-1}. In other words, the harvesting of wheat straw with SLW considering a transport distance of 5 km involves a reduction of almost 50% of the field capacity if compared with the unloading of the biomass directly on the field. A transport distance of 50 km is equivalent to a loss of field capacity of 91% compared to the discharge of biomass on the field (0.38 ha h^{-1}). In the case of maize stalk, the field capacity of the SLW is halved at a distance of 8 km between the field and the IBLC, passing from 1.31 ha h^{-1} to 0.66 ha h^{-1}, respectively.
In general, the field capacity of the harvesting system "B" with SLW for both agricultural residues was halved within the first few kilometers distance from the field to the IBLC, and in particular, at a distance of 10 km, there were reductions in the field capacity of 66% and 55% for wheat straw and maize stalks harvesting systems, respectively (Figure 2).

The study focused on evaluating the system that best suits the real needs of a Spanish company that will use the residual biomass to produce energy, starting from the equipment normally uses for IBLC business.

However, the implementation of a model to determine the number of vehicles that would be needed to ensure a continuous harvest as, for example, proposed by Brownell 2012, will be important for future analysis.

Fuel consumption is a key result in Table 3. The fuel consumption per area unit for straw harvesting resulted generally lower than the harvesting of corn stalks. This is essentially because the residues harvested in the wheat field were smaller, and therefore, the machines processed less material than in the maize field. Even if the fuel consumption of the only harvesting phase was higher for the self-loading wagon respect to the tractor with baler, considering also the consumption of the bales uploading phase, no statistically significant differences were found between the two harvesting systems for each cereal residue per area unit (L ha^{-1}). On the other hand, comparison of the hourly fuel consumption of the maize stalks harvest with the two methods was statistically significant, contrary to what was observed for straw (Table 3 and Figure 3). Straw baling and loading bales together consumed a quantity of fuel similar to the self-loading wagon (Figure 3). The harvesting of straw with a self-loading wagon at high speed resulted in higher consumption compared to what was measured during the harvesting of the corn stalks. However, the differences in fuel consumption obtained from the individual comparison of the harvesting stages of maize stalks and wheat straw (e.g., SLW maize stalk vs. SLW cereal straw) were always statistically not significant.

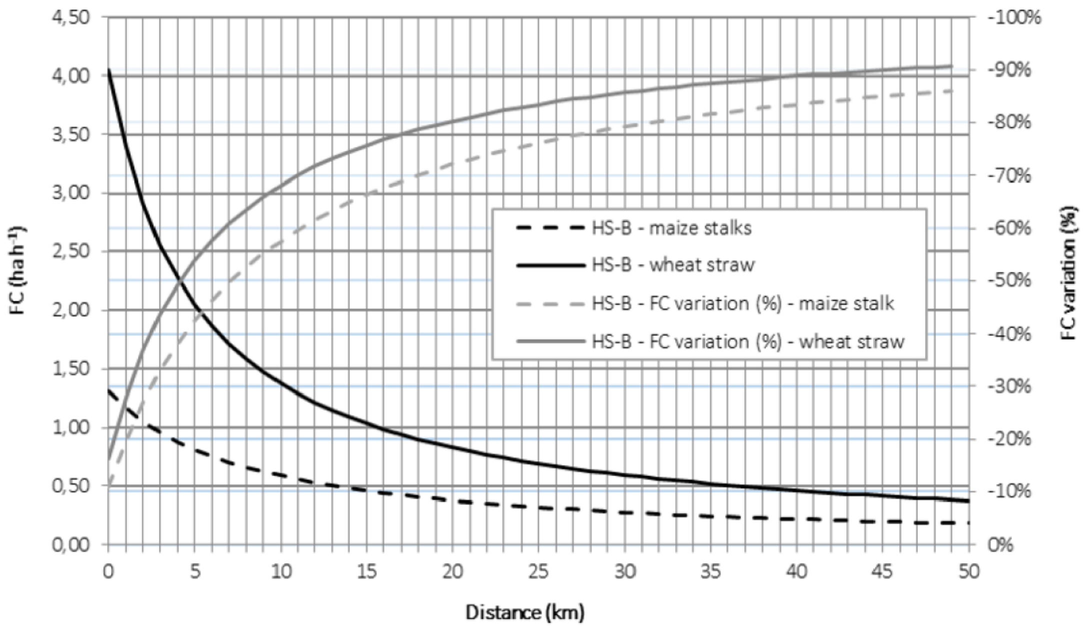

Figure 2. Trend in field capacity (FC) of the harvesting system "B" (HS-B) and its percentage variation in relation to transport distance for both wheat straw and maize stalks.

The comparison of the fuel consumed per product unit for both the maize stalks and cereal straw harvest with the two harvesting methods resulted not statically significant as well.

The transport of the product to the IBLC by SLW showed the highest hourly consumption. The transport of cereal straw with SLW showed an increase in fuel consumption of 22.9% compared to the tractor with bale trailer. In the case of the transport of maize stalks via SLW, the fuel consumption

was even 52.5% higher (Table 3 and Figure 3).

Table 3. Consumption measured during harvesting and transport of maize stalks and wheat straw.

Biomass Type		**Maize Stalk**			**Wheat Straw**	
Harvesting System	**HS-A**	**HS-B**	$p < 0.05$	**HS-A**	**HS-B**	$p < 0.05$
Fuel consumption per area unit						
Harvesting ($l\ ha^{-1}$)	6.42 (±1.05)	9.42 (±1.12)		2.96 (±0.44)	4.59 (±0.88)	
Bales loading ($l\ ha^{-1}$)	5.44 (±1.63)	n/a		1.43 (±0.19)	n/a	
Fuel consumption per product unit						
Harvesting ($l\ t^{-1}$)	0.97 (±0.31)	1.40 (±0.37)		1.25 (±0.28)	1.97 (±0.35)	

Bales loading (l t^{-1})	0.83 ($\pm$0.36)	n/a		0.60 ($\pm$0.12)	n/a
Fuel consumption per hourly time					
Harvesting (l h^{-1}) Bales loading (l h^{-1})	14.45 ($\pm$1.37) 13.03 ($\pm$4.47)	15.13 ($\pm$3.09) n/a	*	13.82 ($\pm$2.05) 8.14 ($\pm$1.95)	21.14 ($\pm$3.69) n/a
Transport (l h^{-1})	12.40 ($\pm$0.91)	18.91 ($\pm$2.47)		16.73 ($\pm$1.74)	20.56 ($\pm$1.04)

* Values marked with asterisks are significantly different ($p < 0.05$) (per parameter per residue type).

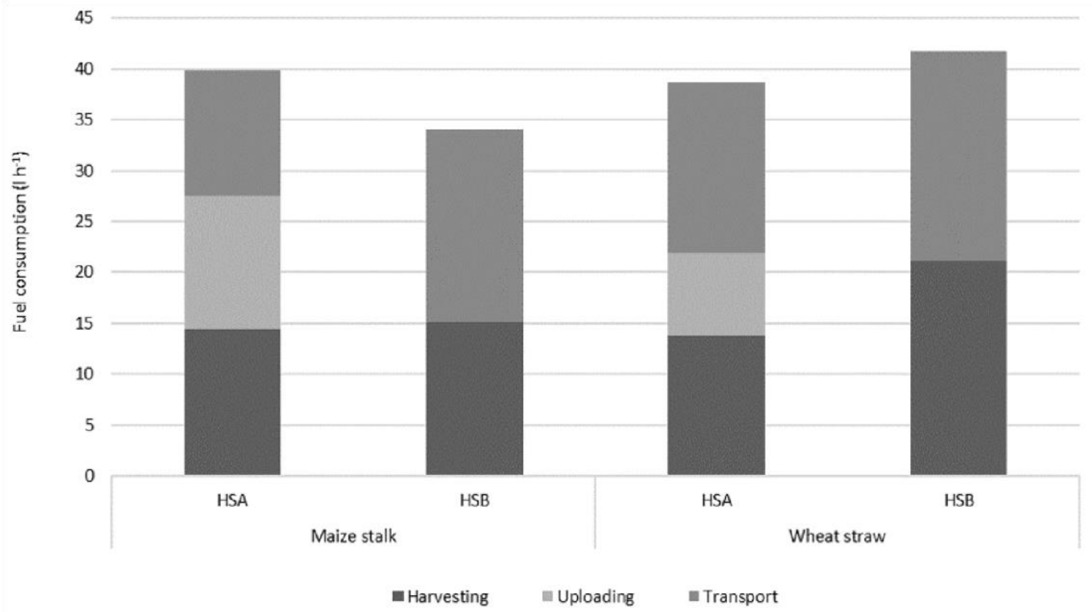

Figure 3. Fuel consumption of the harvesting system "A" (HS-A) and harvesting system "B" (HS-B) for wheat straw and maize stalks.

3.2. Cost Analysis

The cost analysis highlighted that the baling system (HS-A) is more expensive than the harvesting system based to the self-loading wagon (HS-B) (Table 4). In particular, the total hourly cost and the unitary cost of the HS-B to collect maize stalk were 57% and 54% lower than the cost for the HS-A, respectively. Wheat straw harvesting with HS-B presented a total hourly cost and the unitary cost of 53% and 42% higher than the cost of the HS-A, respectively. Variable costs in all cases had the greatest impact on total hourly cost (about 65%), reaching values of more than 70% for straw collection with HS-B.

Table 4. Cost analysis of the harvesting system "A" (HS-A) and harvesting system "B" (HS-B) for wheat straw and maize stalks.

			Harvesting System "A"		Harvesting System "B"	
	Baling	Uploading	Total Harvesting	Transport	SLW	Transport
Financial costs (€)	152,000	72,000	224,000	82,000	150,000	
Wheat straw						

Fixed costs (€ h^{-1})	37.7	8.6	46.3	13.7	13.7	
Variable costs (€ h^{-1})	36.7	20.6	57.3	26.5	35.5	35.1
Total hourly costs (€ h^{-1})	74.4	29.2	103.6	40.2	49.1	48.8
Unitary costs (€ Mg^{-1})	6.6	2.4	9.0	0.34 *	5.23	1.02
Maize stalks						
Fixed costs (€ h^{-1})	37.7	8.6	46.3	13.7	13.7	
Variable costs (€ h^{-1})	37.0	23.4	60.4	24.0	32.0	34.2
Total hourly costs (€ h^{-1})	74.7	32.0	106.7	37.7	45.7	47.8
Unitary costs (€ Mg^{-1})	6.7	2.6	9.3	0.32 **	4.24	0.61

* round trip cost € Mg^{-1} km^{-1} considering a measured average speed of 18.2 km h^{-1} and an average load of 6.5 t of wheat straw bales transported per trip. ** round trip cost € Mg^{-1} km^{-1} considering a measured average speed of 22.9 km h^{-1} and an average load of 5.1 t of maize stalk bales transported per trip.

Furthermore, maize stalks harvesting phase with the HS-A resulted more expensive than wheat straw harvesting with HS-A of almost 3%.

The study showed that the most suitable system for collecting cereal and corn residues is the self-loading wagon if the transport of the biomass to IBLC is not included.

The transportation completely influences the final cost of the residue, and the transport method should be chosen carefully. The dynamic simulation of straw harvesting systems based on conventional high-density bales carried out by Nilsson (2000) demonstrated that longer transport distances and lower straw yields per hectare (<4 Mg ha^{-1}) were the main reasons for the higher costs of straw handling in Sweden [31]. According to our results, bales transport resulted more chip than using the SLW in Spain. The cost to harvest and transport the maize stalks resulted 9.62 € Mg^{-1} using the HS-A and 4.85 € Mg^{-1} using the HS-B, with a transport cost of 0.32 and 0.61 € Mg^{-1} km^{-1}, respectively

(Table 4). The wheat straw transport costs resulted slightly higher than stalks reaching values of 1.02 € Mg^{-1} km^{-1} if the self-loading wagon is used for the transportation of the straw to the IBLC.

According to Brownell (2012), the wagon system is efficient when harvesting dry biomass within 8 km travel distance. For longer distances, a large square baler might be a better option as it can produce 63 large square bales of straw every hour, equal to almost 16 Mg h^{-1} at 13% of moisture content, in line with Kemmerer (2011) that obtained a material capacity of 13 Mg h^{-1} of wet mass [32].

Figure 4 depicts the maximum distance to the IBLC from which it is more economically convenient to gather the biomass in bales instead of using a self-loading wagon per each residue type. According to our results, the transition distance has been identified in 11.4 km and 16.0 km, with a total harvesting and transport cost of 15.8 € Mg^{-1} km^{-1} and 14.1 € Mg^{-1} km^{-1}, for wheat straw and maize stalk respectively. The higher bulk density of loose maize stalks compared to straw (89.3 kg m^{-3} and 18.6 kg m^{-3}, respectively) has had a significant influence on the results of the economic distances to gather the residual biomass of stalk and straw.

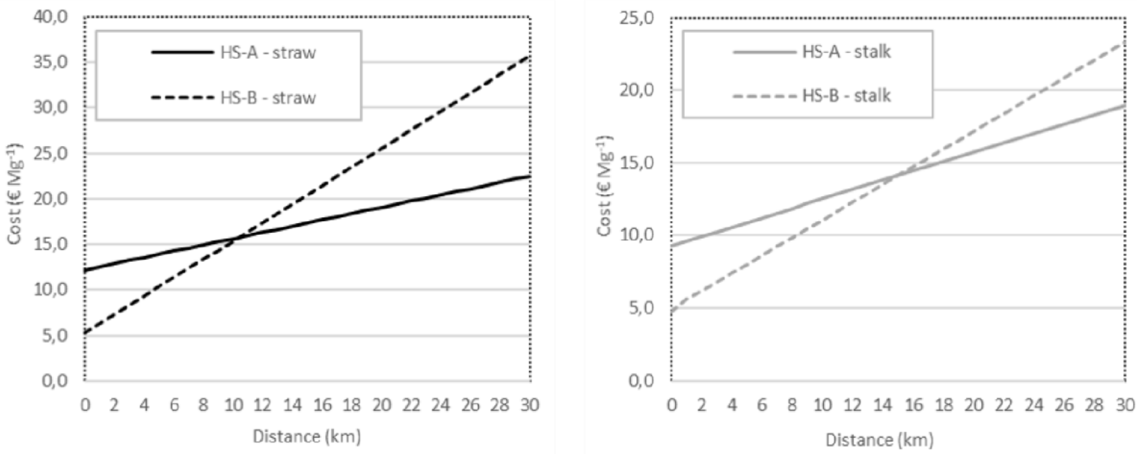

Figure 4. Economic thresholds of the transport of wheat straw and maize stalks by the use of harvesting system "A" (HS-A) and harvesting system "B" (HS-B) in Spain.

As observed by Lizotte (2014) final packaging format (rectangular bales, round bales, chopped bulk material) also plays an important role on storage costs and for this reason this is another aspect that should be consider in future analysis [33].

Furthermore, according to Khan Mubeen (2012) crops grow by utilizing the minerals from soil. When crops are harvested the mineral contents of the soil are also lost, and thus the supplementation of synthetic fertilizers is required [34,35]. Moreover, only a certain number of tons can safely be removed per hectare per year, to avoid erosion phenomenon and fertility reduction effects. For this reason, even if this aspect was not analyzed in this study, in addition to the direct costs incurred in collecting, handling, and hauling the stalks and straw, farmers will expect compensation for the nutrients removed, and this aspect should be included as well for the evaluation of the sustainability of the supply chain of residues.

4. Conclusions

Corn stalks and wheat straw are less costly than growing a dedicated energy crop because they are produced as a co-product of grain production, and no additional cost, other than the harvest and nutrient replacement, is required to produce the residues. However, estimating the cost of harvesting residues is not straightforward and depends on which harvest methods are used, the equipment, the amount of biomass removed per hectare, and the storage and transportation method.

The scope of this research was to evaluate the cost of logistics in the harvest of cereal straw and maize stalks, considering two harvest systems (baling vs. self-loading wagon). According to the parameters analyzed, the use of the self-loading forage wagon resulted more convenient for both wheat straw and maize stalks up to a distance of 11.4 km and 16.0 km, respectively, from the delivery point; after this threshold, it results more convenient the use of balers and trucks for bale transport. As the parameters utilized in this study were specific, results should be interpreted taking into account that the variation of one parameter can influence the final results. However, in general terms, the study fully demonstrated that when considering short distances from logistic centers the use of self-loading wagons should be preferred to the baling, and vice versa for longer distances, the densification in bales will be more effective in economic terms.

It is important to conclude this paper stressing that in the selection of the harvest systems another important aspect is the storage. This will require deeper attention in the future as storage of biomass can determine economic losses or additional costs due to reasons such as the degradation of the dry matter, the need of covering systems, and space availability. Further studies will be performed to evaluate storage dynamics and related-costs in a way to provide a complete analysis of the wheat straw and maize stalk logistics.

Aspects related to cost estimation of storage and nutrients to be returned to the soil and the damage due to possible erosion phenomena related to the removal of residues should be investigated and included in future studies.

Author Contributions: Data curation, A.S. (Alessandro Suardi), S.B., V.A. and A.S. (Antonio Scarfone); Funding acquisition, L.P.; Investigation, A.S. (Alessandro Suardi), S.B., V.A. and A.S. (Antonio Scarfone); Methodology, A.S. (Alessandro Suardi), S.B., V.A. and A.S. (Antonio Scarfone); Project administration, L.P.; Writing–original draft, A.S. (Alessandro Suardi), S.B., V.A. and A.S. (Antonio Scarfone).

Funding: This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No 727961.

Acknowledgments: The work was performed in the framework of the European project AGROinLOG "Demonstration of innovative integrated biomass logistics centres for the Agro-industry sector in Europe". The authors wish to thank the employees of Agroindustrial Pascual Sanzfirm (Zaragoza, Spain) for the authorization to conduct the tests and for their assistance in performing them and their professionality and availability.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Scarlat, N.; Dallemand, J.F.; Banja, M. Possible impact of 2020 bioenergy targets on European Union land use. A scenario-based assessment from national renewable energy action plans proposals. *Renew. Sustain. Energy Rev.* **2013**, *18*, 595–606. [CrossRef]
2. Buratti, C.; Barbanera, M.; Fantozzi, F. A comparison of the European renewable energy directive default emission values with actual values from operating biodiesel facilities for sunflower, rape and soya oil seeds in Italy. *Biomass Bioenergy* **2012**, *47*, 26–36. [CrossRef]
3. Sathre, R. Comparing the heat of combustion of fossil fuels to the heat accumulated by their lifecycle greenhouse gases. *Fuel* **2014**, *115*, 674–677. [CrossRef]
4. Ghaderi, H.; Pishvaee, M.S.; Moini, A. Biomass supply chain network design: An optimization-oriented review and analysis. *Ind. Crops Prod.* **2016**, *94*, 972–1000. [CrossRef]
5. Lal, R. World crop residues production and implications of its use as a biofuel. *Environ. Int.* **2005**, *31*, 575–584. [CrossRef] [PubMed]
6. Scarlat, N.; Martinov, M.; Dallemand, J.F. Assessment of the availability of agricultural crop residues in the European Union: Potential and limitations for bioenergy use. *Waste Manag.* **2010**, *30*, 1889–1897. [CrossRef] [PubMed]
7. Blanco-Canqui, H. Crop residue removal for bioenergy reduces soil carbon pools: How can we offset carbon losses? *Bioenergy Res.* **2013**, *6*, 358–371. [CrossRef]
8. Eleki, K.; Cruse, R.M.; Rogovska, N.; Fodor, L.; Szabó, L. Soil and crop management and biomass removal effects on soil organic matter content in Hungary. *Stud. Agric. Econ.* **2014**, *116*, 107–113. [CrossRef]
9. Nelson, R.G. Resource assessment and removal analysis for corn stover and wheat straw in the Eastern and Midwestern United States—Rainfall and wind-induced soil erosion methodology. *Biomass Bioenergy* **2002**, *22*, 349–363. [CrossRef]
10. Ericsson, K.; Nilsson, L.J. Assessment of the potential biomass supply in Europe using a resource-focused approach. *Biomass Bioenergy* **2006**, *30*, 1–15. [CrossRef]
11. Johnson, J.F.; Allmaras, R.R.; Reicosky, D.C. Estimating source carbon from crop residues, roots and rhizodeposits using the national grain-yield database. *Agron. J.* **2006**, *98*, 622–636. [CrossRef]
12. Wilhelm, W.W.; Johnson, J.M.F.; Hatfield, J.L.; Voorhees, W.B.; Linden, D.R. Crop and soil productivity response to corn residue removal. *Agron. J.* **2004**, *96*, 1–17. [CrossRef]
13. Iakovou, E.; Karagiannidis, A.; Vlachos, D.; Toka, A.; Malamakis, A. Waste biomass-to-energy supply chain management: A critical synthesis. *Waste Manag.* **2010**, *30*, 1860–1870. [CrossRef] [PubMed]

14. Yazan, D.M.; van Duren, I.; Mes, M.; Kersten, S.; Clancy, J.; Zijm, H. Design of sustainable second-generation biomass supply chains. *Biomass Bioenergy* **2016**, *94*, 173–186. [CrossRef]
15. Carriquiry, M.A.; Du, X.; Timilsina, G.R. Second generation biofuels: Economics and policies. *Energy Policy* **2011**, *39*, 4222–4234. [CrossRef]
16. Blanco-Canqui, H.; Lal, R. Soil and crop response to harvesting corn residues for biofuel production. *Geoderma* **2007**, *141*, 355–362. [CrossRef]
17. Kretschmer, B.; Allen, B.; Hart, K. *Mobilising Cereal Straw in the EU to Feed Advanced Biofuel Production*; Institute for European Environmental Policy: London, UK, 2012.
18. Kadam, K.L.; McMillan, J.D. Availability of corn stover as a sustainable feedstock for bioethanol production. *Bioresour. Technol.* **2003**, *88*, 17–25. [CrossRef]
19. AGROinLOG Demonstration of Integrated Biomass Logistic Centres (IBLC) for Food and Non-Food Products. Available online: http://agroinlog-h2020.eu/en/home/ (accessed on 25 May 2018).
20. Onofri, A. Routine statistical analyses of field experiments by using an Excel extension. In Proceedings of the 6th National Conference of the Italian Biometric Society, Pisa, Italy, 20–22 June 2007; Volume 2022.
21. Assirelli, A.; Croce, S.; Acampora, A.; Civitarese, V.; Suardi, A.; Santangelo, E.; Pari, L. An innovative system for conditioning biomass sorghum [*Sorghum bicolor* (L.) Moench]. *Trans. ASABE* **2013**, *56*, 829–837.
22. Pari, L.; Suardi, A.; del Giudice, A.; Scarfone, A.; Santangelo, E. Influence of chipping system on chipper performance and wood chip particle size obtained from peach prunings. *Biomass Bioenergy* **2018**, *112*, 121–127. [CrossRef]
23. International Organization for Standardization. *Solid Biofuels—Determination of Moisture Content—Oven Dry Method—Part 2: Total Moisture—Simplified Method*; Tehnical Report EN ISO 18134-2:2017; International Organization for Standardization: Geneva, Switzerland, 2017.
24. International Organization for Standardization. *Solid Biofuels—Determination of Bulk Density*; Tehnical Report No. ISO 17828:2015; International Organization for Standardization: Geneva, Switzerland, 2015; p. 8.
25. Assirelli, A.; Pignedoli, S. Costo di esercizio delle macchine agricole. *Centro Ricerche e Produzione Animale* **2005**, *5*, 1–10.
26. ASAE. *Agricultural Machinery Management*; Tehnical Report No. ASAE EP496.2; ASAE Stand: Washington, DC, USA, 2000; pp. 344–349.
27. Edwards, W. Estimating a Value for Corn Stover. 2007. Available online: https://www.extension.iastate.edu/AGDm/crops/pdf/a1-70.pdf (accessed on 7 August 2019).
28. Brownell, D.K.; Liu, J.; Hilton, J.W.; Richard, T.L.; Cauffman, G.R.; Macafee, B.R. Evaluation of two forage harvesting systems for herbaceous biomass harvesting. *Trans. ASABE* **2012**, *55*, 1651–1658. [CrossRef]
29. Lizotte, P.L.; Savoie, P. Harvesting residual corn stover with a self-loading wagon for animal bedding. In Proceedings of the 2011 American Society of Agricultural and Biological Engineers, Louisville, KY, USA, 7–10 August 2011; p. 1.
30. Lizotte, P.L.; Savoie, P. Spring harvest of corn stover for animal bedding with a self-loading wagon. *Appl. Eng. Agric.* **2013**, *29*, 25–31. [CrossRef]
31. Nilsson, D. Dynamic simulation of straw harvesting systems: Influence of climatic, geographical and biological factors on performance and costs. *J. Agric. Eng. Res.* **2000**, *76*, 27–36. [CrossRef]
32. Kemmerer, B.D.; Liu, J. Comparison of large square bale handling options. In Proceedings of the 2011 American Society of Agricultural and Biological Engineers, Louisville, KY, USA, 7–10 August 2011; p. 1.
33. Lizotte, P.L.; Savoie, P.; Khelifi, M. Cost Analysis of corn stover harvested in the spring. In Proceedings of the 2014 American Society of Agricultural and Biological Engineers, Montreal, QC, Canada, 13–16 July 2014; p. 1.
34. Johnson, J.M.F.; Wilhelm, W.W.; Karlen, D.L.; Archer, D.W.; Wienhold, B.; Lightle, D.T.; Laird, D.; Baker, J.; Ochsner, T.E.; Novak, J.M. Nutrient removal as a function of corn stover cutting height and cob harvest. *Bioenergy Res.* **2010**, *3*, 342–352. [CrossRef]
35. Khan, T.S.; Mubeen, U. Wheat straw: A pragmatic overview. *Curr. Res. J. Biol. Sci.* **2012**, *4*, 673–675.