Further Uses of Chaff and Straw

Integrated Weed Management Possibilities in a Minimum Tillage System

A report for

By: Matthew Hill

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Sponsored by:

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Executive Summary

This report was motivated by the increasing prevalence of weed resistance to commonly used agricultural chemicals within Western Australian grain growing areas in general and the Esperance Port Zone in particular.

One means of reducing reliance on agricultural chemicals is to capture weed seeds during the harvesting process and either destroy them as they pass through the harvester or capture them as they leave the harvester, in either the chaff or the combined chaff and straw portions. This not only reduces the number of weed seeds returning to the soil thereby depleting the weed seed bank but also has the potential to unlock extra value to the farmer from exploitation of the chaff and straw yields.

The denaturing of weed seeds using microwave energy as they pass through the header is an exciting and entirely plausible possibility being studied by Dr. Graham Brodie at the Dookie Campus of the University of Melbourne. It is hoped that this technology will one day be developed to the point that it could be incorporated into a harvester.

If harvest residue is to be removed from the field the question, then is what to do with it? The most obvious and least capitally-intensive option is capture chaff in a chaff cart, collect these chaff heaps at a later stage and then pelletize them as animal feed.

Another very exciting option is for farmers to become bio-electrical producers by converting their chaff or straw into power. Electrical energy can be produced from harvest residues either by anaerobic digestion or direct combustion for the production of steam.

Bio Char is an ancient technology gaining increasing attention in a modern world. Bio Char is the charcoaling of organic material via the process of pyrolysis to produce a solid fraction being Bio Char, a liquid fraction being Bio Oil and a gaseous fraction being Bio Gas.

The use of harvest residues in material manufacture to produce paper, cardboard, particle board and high value glycols has a potentially huge global market. Material manufacture is however the most technically challenging and capital intensive of all options considered in this report.

The use of microwave energy for the denaturing of weed seeds during the harvesting process would provide the most elegant solution however at this stage it is still just a concept. It would seem that of all options considered the production of pellets from chaff would be the most economically viable and provide the best fit within a farming context. Producing electricity from straw is a very exciting prospect however the economics are still in question. It does however appear viable, and deserves further investigation.

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Foreword

I farm in the Beaumont area east of Esperance with my wife Angela and two children James and Lucy. We form part of a family partnership along with Ted and Rachel Young, my wife's parents, and Michael and Jodi Young my wife's brother and sister in-law. We own and lease an overall arable area of 13,000ha.

The farm has two primary enterprises, being cropping and livestock production. Cropping accounts for 11,000ha annually and includes wheat, barley and canola as the primary crops grown. Legumes only comprise a small area of the cropping program, around 500 to 600 ha annually, and typically consist of field peas or, most recently, vetch. The remaining 2,000ha is rotated to a pasture on which we are running a self-replacing merino ewe flock of some 6,000 to 7,000 ewes mated annually. Angus cattle comprise a small component of the livestock operation with between 100 to 150 cows mated annually.

The soil types on our farm are typical of the area and can be described as duplex soils of sand over alkaline domed clay; other soil types include deep sand, lateritic sandy gravel over clay and alkaline clay loams. The soils are typically low in fertility and trace elements, especially copper and zinc, and range in pH from 4.0 to 8.0.

The farm is situated on the south-eastern coast of Western Australia with the climate being temperate Mediterranean with the majority of rainfall falling over the winter months. The average annual rainfall is between 410mm to 450mm. The growing months are autumn through spring with winters being mild with few frosts.

Farming in my area has traditionally been mixed livestock and cropping however in recent times cropping has become the dominant enterprise.

The Esperance area was an early adopter of "Minimum Tillage" practices. Min Till was introduced in the 1980's and by the end of the 1990's was practically universal in the area. The adoption of Min Till has improved the soils and the economics of cropping to such an extent that cropping is now the most profitable enterprise. With this success, the percentage of land sown to crop rather than pasture increases every year.

However, with the many benefits of Min Till there must be some negatives and the major negative is the potential, and the reality, of weed resistance to chemicals. Within the cropping rotation Min Till is completely reliant on chemical weed control and even with a pasture rotation, weed seed set control is still achieved with chemical, albeit from a different group.

In recent years, there has been recognition of this potential for chemical resistance and attempts are being made to address it utilizing non-chemical weed control techniques. The most common of these include the use of chaff carts (wagons), baling crop residue, windrow burning of crop residue and most recently the pulverizing of weed seeds as they exit the harvester using the Harrington Seed Destructor ™. All these methods are valid and effective however they all suffer from the same limitation. They are largely capital or labor intensive and provide no financial return, beyond the reduction in weeds seeds, for the effort.

It is important to clarify here, that as an advocate for Min Till practices, I believe that the single best use for crop residue is to return that residue to the field. The only caveat to returning residue to the soil being that so long as it does not add to the weed burden and therefor to the pressure on weed resistance. Therefor the two options available are to either remove the weed seeds, e.g. chaff carts, or to denature that seed, e.g. the Harrington Weed Destructor. The use of crop residues for commercial purposes is not new and has been employed in many other parts of the world for many years. Traditional uses include the baling of straw for power generation, bedding for animal housing, composting or pelletizing for fodder or power.

The purpose of my Nuffield Scholarship was to travel the world, home and abroad, to search out innovative uses for crop residues, if they are to be removed from the field, or innovative means to denature that residue if it is to remain in the field.

Acknowledgments

I would like to thank, first and foremost, my wife, Angela, and children James and Lucy. Without their love and support this wonderful journey would not have been possible.

To Ted, Rachel, Michael and Jodi Young for their love and encouragement, for putting up with my extended absences and for supporting my family while I was away, my deepest gratitude.

To the GRDC and specifically Brondwen McClean and Teri-Ann Fewson for their sponsorship of my study and their kind support.

I would especially like to thank the global network of Nuffield Scholars who generously gave of their time and knowledge, provided accommodation, meals and laundry facilities.

Finally, to my Global Focus Program brothers, Lachie Seears, Paul Green, Ed Green, Paul Inderbitzen, Joe Muscat, Paul Serle, Tafi Manjala, Trent De Paoli and Blake Vince who made this Nuffield experience an adventure of a lifetime.

Figure 1: GFP Crew CYMTT Obregon Mexico and bogged in the Brazilian Cerrado.

Abbreviations

Ac	Acre
AD	Anaerobic Digestion
Bu	bushel
CHP	Combined Heat and Power
EPZ	Esperance Port Zone
GHz	Gigahertz
GMO	Genetically Modified Organism
GRDC	Grains Research and Development Commission
Ha	Hectare
Hp	horsepower
Hr	Hour
Kg	kilogram
kJ	kilojoule
kW	kilowatt
kWhr	kilowatt hour
Min Till	Minimum Tillage
Mm	millimetre
MW	mega Watt
NSZ	Nitrogen Sensitive Zone
Sec	Second
T	metric tonne
Tpa	tonnes per annum
WA	Western Australia

Conversions

Exchange Rates: GBP£1 =AU$1.60
CA$1 =AU$1.08
US$1 =AU$1.25

Objectives

"If herbicides were the complete answer to weed control, we would have eradicated annual ryegrass and wild radish from Australian cropping systems long ago."

(GRDC, 2013)

The prime objective of this study is to assess new ways to reduce reliance on chemical weed control through the removal of viable weed seeds from the cropping system during the harvesting process. This report considers two ways to achieve this goal. Either denature the weed at the time of harvesting and leave all crop residue in-situ or remove either the chaff component or the combined chaff and straw component from the field and value add to that component.

The areas that have been studied as part of this report are;

a) In-situ denaturing of weed seeds, including the potential for the use of microwave energy in weed eradication.
b) The removal of chaff and/or straw and its further uses, including;
    - The production of fodder pellets from chaff,
    - Bio energy production in the Esperance Port Zone,
        - Straw fired power plants and
        - Anaerobic digesters,
    - Biochar and its potential and
    - Agricultural residues for material manufacture.

Introduction

This report relates to the agricultural situation experienced within the Esperance Port Zone (EPZ) located on the south-east coast of Western Australia (WA). The findings of this report would however be relevant to most of the remainder of the Western Australian wheat belt or any other agricultural region that relies predominately on Min Till cropping systems with little or no other diversification. The total arable area of the EPZ is 1,300,000 Ha (Western Australian Department of Agriculture and Forestry, 2011) with the area being planted to crops in 2013 being 1,022,000 Ha and the remaining 278,000 Ha being utilized for pasture and tree plantations. Sheep and cattle production are the dominant enterprises on pasture. A summary of EPZ arable land use is included in Table 1 below.

Table 1: Esperance Port Zone - Arable land use				
	2013	2010	2005	2000
Wheat	446,000 Ha	432,000 Ha	266,000 Ha	212,000 Ha
Barley	250,000 Ha	280,000 Ha	172,000 Ha	110,900 Ha
Canola	281,000 Ha	186,000 Ha	89,000 Ha	94,900 Ha
Oats	4,000 Ha	4,000 Ha	7,000 Ha	6,600 Ha
Lupins	16,000 Ha	19,000 Ha	18,000 Ha	23,500 Ha
Field Peas	25,000 Ha	50,000 Ha	27,000 Ha	5,200 Ha
Tree Plantation	50,000 Ha	50,000 Ha		
Pasture/Other	228,000 Ha	246,000 Ha	721,000 Ha	846,900 Ha
Total Crop	1,072,000 Ha	1,054,000 Ha	579,000 Ha	453,100 Ha
Total Area	1,300,000 Ha	1,300,000 Ha	1,300,000 Ha	1,300,000 Ha

Source: (Grain Industry Association of WA, 2000,2005,2010,2013)

As can be seen from Table 1, the EPZ in 2013 is relying on only three crop species, wheat, barley and canola, grown in a tight rotation accounting for 78.6% of non-forested arable land. A pasture rotation of 228,000Ha constitutes 14.2% of non-forested area. Crop legumes constitute a minor 4.1% of the crop grown, excluding forestry, and 4.0% of the total rotation including pasture.

This is in stark contrast to the situation in the year 2000 when only 34.8% of the arable land in the EPZ was planted to crop with the remaining 65.2% being farmed as a pasture. The proportion of legumes within the crop rotation remains similar at 6.3%.

This concentration of cropping is using a limited rotation of two cereals and one brassica and therefore there is a heavy reliance on a limited number of agricultural chemical pesticides for weed control in a Min Till system. This demonstrates the need for the introduction of non-chemical weed control or alternative crops within the rotation, that either use alternative chemical or non-chemical weed control.

An example of non-chemical weed control would be to either denature any weed seeds present in the crop during the combining process or to collect those weed seeds and remove them from the field as either chaff or chaff and straw for use as animal fodder or the production of energy.

An example of an alternative crop to introduce into the rotation would be one that could be used as silage or hay. Silage and hay provide good weed control by cutting prior to weed seed set and the collection of any such weeds in the process. In the absence of feed demand for livestock, silage and hay may be used for the production of energy.

WA farmers were early adapters of Min Till from its initial uptake in the early eighties to the current situation where over 90% of WA farmers practice Min Till at present (Llewellyn, 2010). Min Till farming minimizes or eradicates the use of tillage for weed control relying instead on agricultural weedicides. This increased reliance on chemical weed control and the increased exposure of these weeds to those chemicals, due to the increased proportion of cropping within a rotation, increases the probability of those weeds developing resistance.

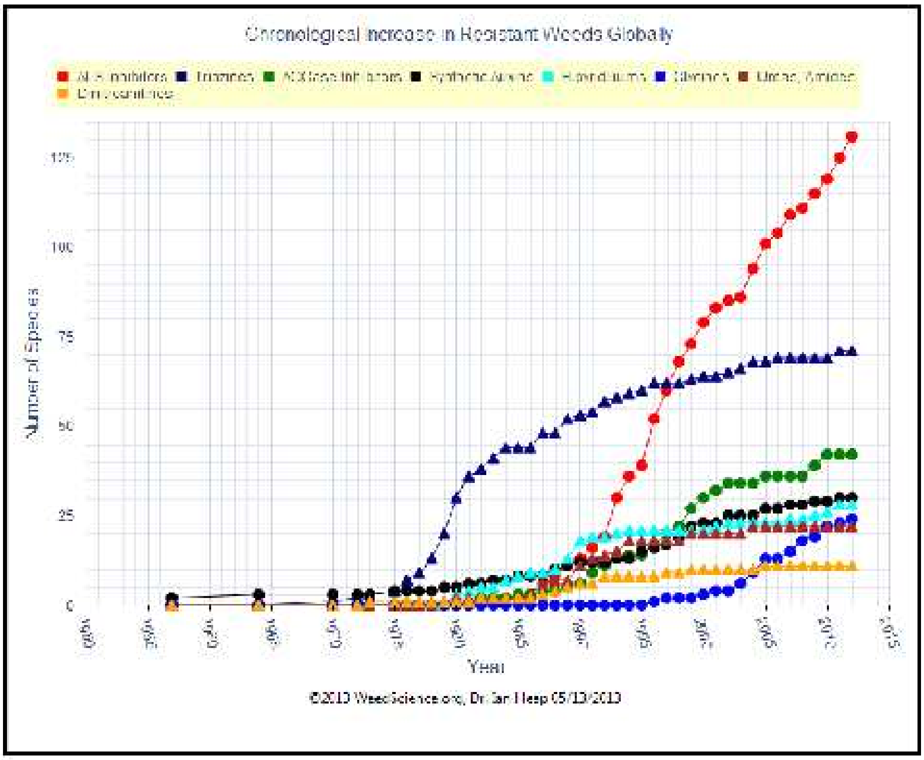

Figure 2 - Chronological Increase in Resistant Weeds Globally

Source: (Heap, 2013)

Within Australia weed resistance is developing to many chemicals. Groups A (ACCase Inhibitors) and B (ALS Inhibitors) are considered at high risk of developing resistance. Group M (Glycines/Glyphosate) is considered at moderate risk of developing resistance (Crop Life Australia, 2013). Figure 2 shows the increase in resistant weeds reported globally.

Of concern in Figure 2 is the emergence of resistance to Glycines in the last decade. Glyphosate is a Glycine and is the single most important agricultural chemical for the control of weeds in a Min Till system.

The removal of the moratorium on growing GMO (Genetically Modified Organisms) canola in Western Australia in 2010 has seen the steady introduction of these crops into the farming system in W.A. broadly and the EPZ specifically. GM Canola has been modified to be resistant to Glyphosate thereby providing a weed control option over weeds that have developed resistance to ACCase Inhibitors and Triazines. Hence Glyphosate is going to be used more broadly and will be relied on more exclusively for weed control into the future.

The following table, Table 2, summarizes the number of varieties of resistant weeds by country and the number of glyphosate resistant weeds in order of magnitude.

Table 2: Herbicide resistant weed populations by country		
	Total	Group G
United States	143	14
Australia	62	6
Canada	59	4
China	34	2
France	34	1
Spain	33	5
Brazil	31	5

Source: (Heap, 2013)

The United States of America (USA), Australia and Canada are developing significant resistance to herbicides and Glyphosate in particular. In Chatham-Kent area of Southern Ontario, Canada, the standard rotation in the area is GMO Corn followed by GMO Soy and then a conventional winter wheat. GMO corn and soy have been genetically modified to be resistant to glyphosate. It has been discovered that the consequent extended use of glyphosate over many years has resulted in the requirement for increased application rates of glyphosate to maintain control over most weeds or the actual development of resistance in others. Local farmer, Mr. Blake Vince, reported that common rates of glyphosate required for effective weed control are in the order of 5-6 l/ac (12-15 l/Ha) seasonally and weeds species that have developed complete resistance to glyphosate in this region include Giant Rag Weed, Fleabane and Palmer Amaranth. All this has occurred in a region that uses cultivation as a primary means of weed control (Vince, 2013).

Dr. Carol Mallory-Smith (Dr. Mallory-Smith, 2013) states that this level of resistance in Ontario is reflected throughout the grain growing areas of the USA and was the inevitable consequence of farmers relying on a single chemical for weed control. Dr. Smith advises that for the Western Australian experience where the use of GMO's is still in its infancy that farmers should still use effective pre-sowing/pre-emergence chemicals even when using glyphosate resistant GMO's to reduce the probability of resistance developing to glyphosate. This is especially pertinent given that Australia is second only to the USA in the development of resistance to Group G herbicides.

Efforts to combat the emergence of chemical resistance are being undertaken by many farmers within the EPZ utilizing many different techniques. With specific regard to capturing weed seeds the single most popular technique is the use of chaff wagons to capture and dump the chaff in discrete piles throughout to field. These piles of chaff are then burnt at a later stage. Figure 3 shows the accelerated reduction in Ryegrass plant population achieved by incorporating harvest weed seed control.

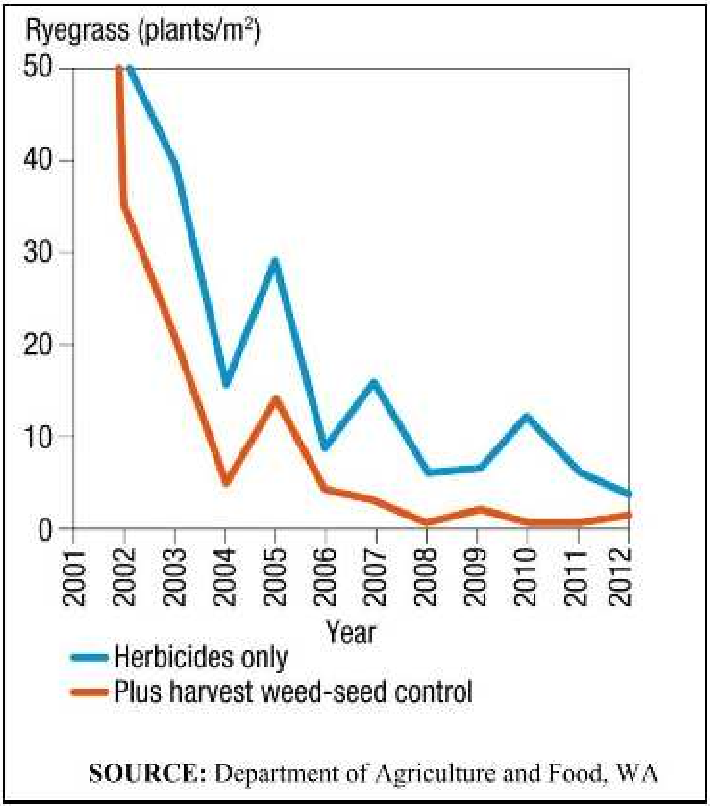

Figure 3 - Reduction in Ryegrass Plant Numbers When Using Harvest Weed Control Source: (GRDC, 2013)

There have been isolated incidences of residue baling however this has not proved popular as there is simply no purpose or use for the baled residue and the volume of material makes it difficult to deal with on farm. Herein lays the difficulty within the EPZ for the production of crop residue, there is no local market for the product and Esperance is too isolated to generally make the transport of crop residue to other areas economically viable.

2. In-situ denaturing of weed seeds

The concept of denaturing weed seeds as they exit the combine is perhaps the simplest and most elegant form of weed control as the goal is accomplished in a single pass and all the organic matter from the crop is returned directly to the soil. If you discount any value for the chaff or straw, it may also turn out to be the most cost-effective.

At this point, the only commercial in-situ weed denaturing system is the Harrington Weed Destructor (TM) which had its commercial release in 2012. The HWD consists of an independently powered hammer/cage mill towed behind a combine on its own trailer unit into which chaff is fed, milled and then fed onto rear mounted spreaders to be spread back onto the ground.

While the HWD is an entirely efficient and effective solution its negatives are size, weight, reliability and cost. It is not the purpose of this report to critically analyze the HRD but rather to acknowledge that it is one solution to the problem of weed seed control and search for further solutions.

2.1 Microwave treatment of chaff

Dr. Ian Brodie has been studying the potential uses for commercial microwaves in an agricultural context from the Dookie Campus of the University of Melbourne. Dr. Brodie has developed a prototype machine that consists of 4 commercial 2kW, 2.45GHz microwave generators. The purpose of this machine is to treat living plants (weeds) with microwave energy, thereby killing them as an alternative to chemical spraying.

The microwave energy is directed from the microwave generator, which lies horizontally at the rear of the trailer, through the black horn antennae which directs the microwaves vertically downwards into the weed canopy. The microwave generators are water cooled, which improves their efficiency to 90% (microwave energy emitted/electrical energy consumed). This type of industrial microwave generator also includes a facility for automatic arc detection. This should prevent any arcing and therefor any fire risk if metallic material comes within the treatment zone.

Microwaves are widely used in communications and therefor the microwave spectrum of frequencies is a very busy spectrum. There are four commercial frequencies available for agricultural use including the 2.45 GHz frequency used in domestic appliances. At this stage, there has been no research into using microwaves to directly treat chaff exiting a combine, however it is at least theoretically possible.

Figure 4: Dr. Brodie and his Microwave Machine

Dr. Brodie advises that a frequency of 922 MHz may be the best frequency to use on seeds as the longer the wavelength the more penetration into the seed is achieved. The physical size of a microwave is inversely proportional to its emitted frequency, therefor the lower the frequency the larger the size of the physical microwave generator.

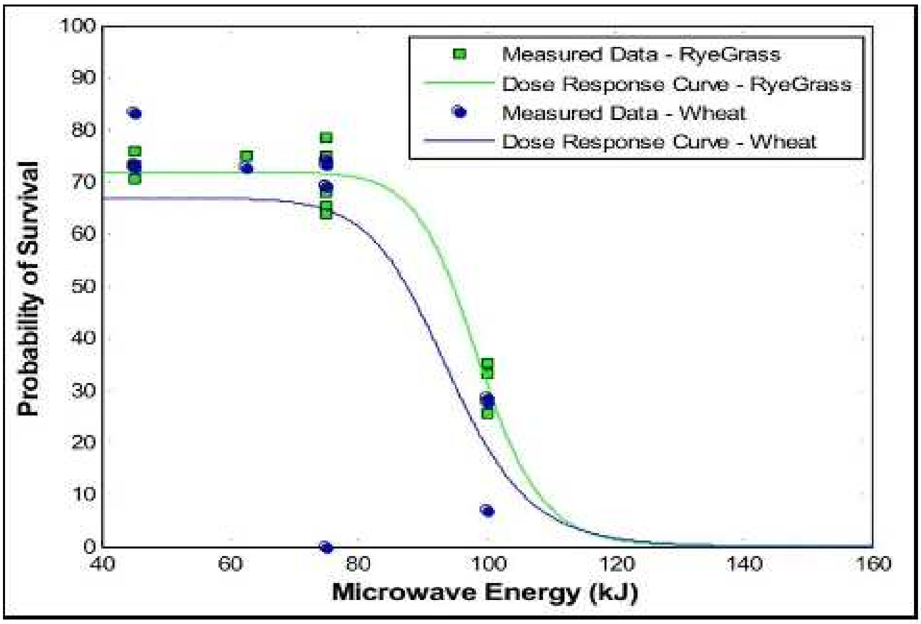

Figure 5: Probability of Seed Survival when Exposed to Microwave Energy Source: (Brodie, 2013)

Figure 5 shows the results from a study "Killing Weed Seeds in Hay" (Brodie, 2013) which assesses the probability of ryegrass and wheat seed survival after exposure of a 1kg sample of hay to differing levels of microwave energy. This study has the greatest relevance to denaturing weed seeds in chaff.

As can be seen from Figure 5, a dose rate of 120 kJ allows for a very low probability of survival. This concept and the data described in Figure 5 were taken to the global CNH combine manufacturing headquarters located in Zedelgem, Belgium, to discuss the future possibility of incorporating a microwave denaturing module within a combine. A meeting was held with Jasper Clarrisse, Harvesting Marketing Director and Bort Missotten, Manager of Innovation, where the following calculation was developed.

Assumptions:

1: 150 kJ/kg microwave energy required to denature weed seed.

2: 10kg/sec chaff produced at 50t/hr harvesting (CNH).

Now; Too denature 1kg of chaff requires 150 kJ

Therefore; Too denature 10kg of chaff requires 1,500 kJ

Now; 1 kW = 1 kJ/sec

Therefor to denature 10kg/sec of chaff;

= 1,500kJ / 1 sec

= 1,500 kW

= 2040 hp (where 1 kW = 1.36 hp)

This power requirement is obviously far too high and needs to be reduced.

First let’s increase the exposure time from 1 sec to 5 sec,

Then power = 1,500kJ/5sec

= 300 kW (408 hp)

This power requirement is still too high. Therefor we need to reduce the quantity treated. For instance, we could separate the weed seeds from the chaff and treat them alone. Assuming weed seeds account for 10% of the mass of chaff,

Then power = 300kW x 10%

= 30kW (41hp)

This then at least brings the power requirement into the realms of practicality.

Figure 6: Calculation of microwave energy required to denature chaff within a combine

The above calculation uses an assumption of 10kg/sec chaff produced while harvesting at a rate of 50 t/hr, this number was used as a worst case scenario to anticipate maximum instantaneous product flows. Nicholas Berry *et al*. (2012) conducted the study, “*Relating the Power Requirement of the Harrington Seed Destructor to Chaff Throughput*”, which suggests a much lower throughput rate of chaff.

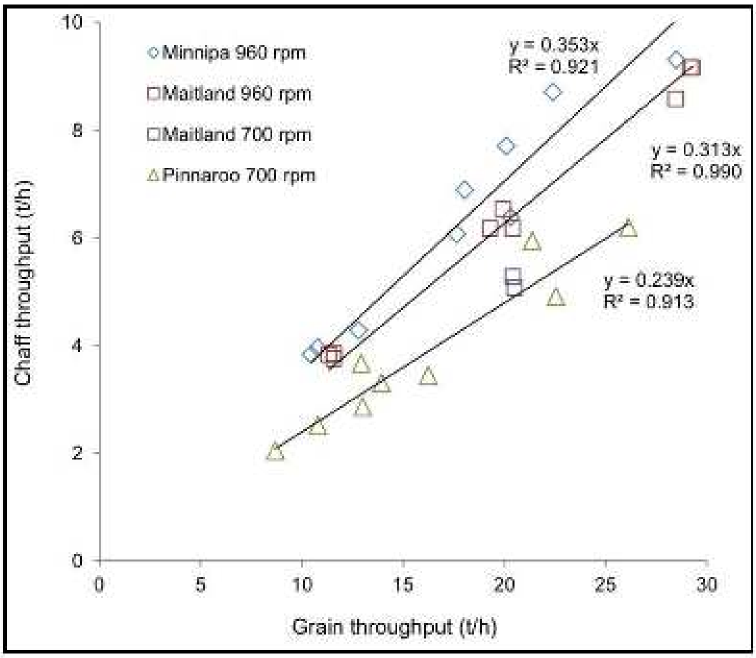

Figure 7: Grain Throughput 'v' Chaff Output

Source: (Berry, Saunders, & Fielk, 2012)

Figure 7 summarizes the results which show that, within specific varieties of wheat, there is a very good correlation between grain throughput and chaff produced. The wheat variety that produced the most chaff in relation to grain was Minnipa, which produced a chaff to grain ratio of 0.353:1 (t/hr : t/hr). If you apply this ratio to a harvesting rate of 50 t/hr we get a chaff rate of 17.65 t/hr which equates to 4.9 kg/sec, half that used to calculate the microwave power requirement. Obviously as there are significant variations in chaff production between different varieties of wheat there will also probably be large variations in chaff production between different crop species, e.g. barley and canola.

The above calculation was submitted to Dr. Brodie, who agreed that the logic was correct and that he is currently in the process of determining ways of reducing the power requirement. Dr. Brodie agrees that increasing exposure time is one way of reducing the power required. However, another mechanism is to compress the material being treated, which appears to greatly increase the heating efficiency. Dr. Brodie says that further trials need to be performed to confirm these assumptions and that he is quite hopeful of achieving good seed deactivation with moderate power requirements of between 30 to 50 kW.

The use of microwave energy to denature weed seeds during the harvesting process is a very exciting concept, elegant in its simplicity, with very little mechanical work required and hopefully a reasonable power requirement. As a comparison Berry *et al* suggest that the power requirement of the HSD is linearly related to chaff throughput which can be estimated using the equation:

$$P = 5.75x + 35.9$$

where P is power in kW and "x" is chaff throughput in t/hr. Hence the estimated power required for the HSD to treat a chaff throughput of 10 kg/sec (36 t/hr) is 242.9 kW. This then at least sets the goal post for the development of the microwave concept.

The use of microwaves is however in its infancy and even if it is a viable concept it will take a long time to develop and bring in to production.

3. The removal of chaff and straw

If the weed seeds cannot be denatured in-situ, then the only other option is to collect them either in the chaff alone, such as is achieved with a chaff cart, or to collect the complete harvest residue and bale the chaff and straw. The issue then is what to do with it?

When removing bio mass from the field you are also moving nutrients. The quantity and value of those nutrients must always be considered and if they are being removed then they should be replaced.

Table 3 below sets out the potential nutrient loss due to the removal of straw, this has been combined with current nutrient prices obtained from CSBP, (2014) and summarised below.

Table 3: Nutrient loss (kg) per tonne of straw removed			
Nutrient	Nutrient Cost ($/kg)	Nutrient Loss (kg)/t of straw	Nutrient Value ($)/t Straw
Phosphorous	2.86	0.5	1.43
Potassium	1.25	10	12.50
Sulfur	0.68	0.5	0.34
Nitrogen	1.36	5	6.80
Total			**21.07**

Source: (Western Australian Department of Agriculture, 2005), (CSBP, 2014)

As can be seen the value of nutrients removed, $21.07/t, is not inconsequential. However, this report presumes that the farmer is already collecting chaff or straw. Given that industry practice at this stage is to burn that material anyway, then those nutrients are already being lost or being concentrated in discreet dump sites or windrows.

3.1 Anaerobic digesters

The process of Anaerobic Digestion (AD) can be broadly described as creating a cow's stomach in a sealed tank. Nutrients are introduced into a sealed tank along with bacteria, the bacteria consume the nutrients and the by-products of the life cycle of these bacteria are a bio gas, primarily methane. The bio gas is drawn off, cleaned, and then delivered to a Combined Heat and Power (CHP) plant. The CHP is a converted diesel engine that drives a generator for the production of electricity. Excess heat from the generating process is fed back to the AD plant to maintain optimum temperatures for the bacteria. Some typical biogas yields are included in Table 4 below.

The byproduct of bio-digestion is called digestate which is the material left over after all other nutrients have been consumed. Disposal of the digestate is an important consideration as it contains nitrogen and other trace elements, depending on the feedstock, and as such has some value as a fertiliser. In the UK if only agricultural wastes, manure and vegetable material is used as a feedstock then the digestate is classified as an agricultural product and can be spread directly onto the field. If, however the feedstock is industrial waste from food processing or manufacture then the digestate is classified as industrial waste and cannot be spread directly onto farming land without treatment. To enable such digestate to be applied to farming land, the feedstock must be pasteurized prior to introduction into the bio digester and a strict regime of testing followed to monitor for E.coli and Salmonella.

Table 4: Typical biogas yields for various feedstocks.

Feedstock	Dry Matter %	Biogas Yield m3/t
Cattle Slurry	10	15-25
Grass Silage	28	160-200
Whole Wheat Crop	33	185
Maize Silage	33	200-220
Straw		242-324
Sorghum		295-372
Wheat Grain		384-426
Canola Meal	90	620

Source: (NNFCC; The Andersons Cenre; IEA)

Figure 8: Wyke's Farms, AD plant under construction

Rodger Wyke of Wyke Farms, located in Somerset, England, is in the process of constructing a 1.2MW bio-digester consisting of two digester domes and one digestate dome. Mr. Wyke runs four 400 cow dairy herds, one pig unit of 9,000 pigs and a cheese manufacturing operation producing 12,000 tonne of cheese per year. The challenge for Mr. Wyke is that he is located within a Nitrogen Sensitive Zone (NSZ) that puts significant restrictions on the disposal of slurry from his dairies and pig unit. For this reason, Mr. Wyke decided to invest in a bio-digester which would use all the nitrogenous waste from his dairies, piggery and cheese manufacturing plant and produce up to 75% of his power needs. The bio digester is expected to cost AUS7.2M for a 1.2 MW/hr capacity plant and according to Mr. Wyke will have a five-year payback period (Wykes, 2013). The UK government provides incentives for bio energy which include a subsidized feed-in tariff scheme. The delivery of electricity into the grid is paid via a tiered tariff, which varies depending on the capacity of the plant. This is described below in Table 5. There is also a Renewable Heat Incentive (RHI) which pays a producer for heat produced from renewable sources and the tariffs for that scheme are described in Table 6.

Table 5: UK feed in tariff rates	
Plant Capacity (kW)	**Feed in Tariff (AU¢/kWhr)**
<250 kW	24.26/kWhr
250 - 499 kW	22.43/kWhr
500 - 5,000 kW	14.78/kWhr

Source:(MacKenzie, 2013)

Table 6: UK R.H.I. feed in tariff rates	
Plant Capacity (kW)	**R.H.I. (AU¢/kWhr)**
<200 kW	11.36/kWhr
200 - 499 kW	9.44/kWhr
>500 kW	3.52/kWhr

Source: (MacKenzie, 2013)

Will Fellows is the Plant Manager of the 2 MW bio-digester of Northwick Estate, located in a disused quarry in Gloucestershire, England. This plant does not use any product or residue from the farm estate, rather using waste from food manufacturing in the local area and either getting the feedstock for free or charging a tipping fee to the processor for disposing of their waste product. Dry feedstocks include coffee grinds, manure and vegetable wastes. Liquid feedstocks include milk, beer ullage, sauces, dips and dressings. Animal byproducts include meat waste and other animal proteins. Typical gas production rates for various feedstocks as reported by Mr. Fellows are included in Table 7 below.

Table 7: Northwick Estate - Biogas yields	
Feedstock	**Biogas Yield (m^3/t)**
Grass Silage	180
Manure	80
Pastry	630
Pies/Sausage Rolls	615
Coffee Grounds	350

Source:(Fellows, 2013)

This highly varied diet of dissimilar feedstocks needs to be carefully managed as the indiscriminate introduction of high energy feedstock, such as pasty and animal proteins, can result in a catastrophic and uncontrollable chain reaction within the bio digester, resulting in overflow or rupture.

Dennis Dick of Seacliff Energy, Leamington, Ontario, runs a similar bio digester using industrial food waste as feedstock for his 1.6 MW plant. The total plant cost was reported to average AU$9,180/kWhr. Seacliff Energy processes 80-100t/day of grocery and foodstuff waste to produce 750 m^3/hr of biogas, averaging 180 m^3 gas/tonne of feedstock. The feed in tariff received is AU$0.1436/kWhr which is not enough to return a profit in its own right. A tip-off fee charged to the suppliers of the feedstock is required to make the operation profitable in its own right (Dick, 2013).

Harold and Christopher Perry, of Perry Farms, Coaldale, Alberta are in the planning stage of developing a 600kW bio-digester. The intention is to feed the plant with cull potatoes from their farming operation and use most of the power generated in their processing operation, with excess power being sold back to the grid. Perry Farms expect the plant to have a total capital cost of AU$5.4 Million (Perry, 2013).

Ag Tech, a bio-digester supply company were approached at the Edinburgh Royal Highland Show to supply a quote on supply and installation on a farm scale plant. The plant discussed was a basic straw fed plant powering a 70 kW/hr generator. This plant would come to a total installed cost of AU$640,000 (AgTech, 2013). A summary of capital costs for bio digester plants is included in Table 8 below.

Table 8: Bio digester capital cost			
Name	**Capacity (kW)**	**Capital Cost (AU$)**	**Cost (AU$) / kWhr**
Ag Tech	70	640,000	9,142
Perry Farms	600	5,400,000	9,000
Wyke Farms	1,200	7,200,000	6,000
Seacliff Energy	1,600	14,688,000	9,180

Before translating this technology to Esperance, the economics of the process need to be considered. A method for estimating the economics of a proposed anaerobic digester plant are described in "Economic Aspects of Biogas Plants" (Ehrmann, 2007). The following table provides a summary of a pessimistic, average and best case scenario for an anaerobic digester in Esperance assuming cereal straw as the feedstock and a feed in tariff of AU$0.104/kWhr (Horizon Power, 2012). This table estimates the income and costs of an anaerobic digester on a per tonne of feedstock basis, the revenue available after this pays for the feedstock and allow for profit.

Table 9: Economic evaluation of an Esperance anaerobic digester				
		Pessimistic	Expected	Best Case
Gas Yield	m^3/tonne	242	283	324
Electrical Yield	kWhr/m^3 BG	1.73	1.94	2.16
Electrical Yield	kWhr	418	549	699
Process Losses	10% kWhr	41.8	54.9	69.9
Electricity for Sale	kWhr	376	494	629
Feed in Tariff	AU$/kWhr	0.104	0.104	0.104
Income	**AU$**	**39**	**51**	**65**
Costs CHP Unit				

Table 9: Economic evaluation of an Esperance anaerobic digester				
Capital Costs	AU$/t	4.6	5.8	7.0
Maintenance	AU$/t	6.1	7.6	9.3
Costs Biogas Plant				
Capital Costs	AU$/t	14.3	17.9	21.8
Maintenance	AU$/t	2.5	3.1	3.9
Total Plant Costs	**AU$/t**	**27.5**	**34.4**	**42**
Plant Revenue	**AU$/t**	**11.50**	**16.60**	**23.00**

Source: (Ehrmann, 2007)

As can be seen from Table 9, the estimated revenue available from Anaerobic Digestion (AD) in the Esperance region ranges from a pessimistic $11.50/t to a best-case scenario of $23.00/t. This is simply not high enough to justify the plant given nutrient losses are valued at $21.07/t (Table 3) not to mention baling and transport costs.

When comparing the power produced from one tonne of straw, which has an absolute calorific value of 14.4 GJ (see Table 10), via AD even the best case suggests 629 kWhr which is equivalent to 2.26 GJ of energy. This is a gross electrical efficiency of 15.7% which is significantly less than the 20-22%gross electrical efficiency that could be expected from a steam turbine power plant (Pratt, 2013).

This should be expected as the process of producing electrical power from straw via anaerobic digestion is effectively taking a product that is already perfectly suited for combustion, putting it through an intermediary process and then combusting it. Any intermediary process, being the life cycle of the bacteria in this case, must consume energy thereby reducing the amount of energy available for the production of electricity.

Anaerobic digestion therefor would seem to be best suited to producing electrical energy from organic material, of higher energy density, that is not suited to direct combustion.

3.2 Straw fired power plants

Power generation from crop residue is big business in the EU and the UK and getting bigger. The two primary forms of power generation include burning of crop residue for heat only or for firing boilers to produce steam for electricity generation.

The two major electrical power producing plants using straw in the UK are the Drax plant and the EPR Ely plant. The Drax plant is a co-fired plant using coal as its primary fuel source and cereal straw as a secondary fuel. Due to the fact that this plant is a coal fired generator converted to accept bio-fuel the cereal straw has to be pelletized so that the bio-fuel can be introduced into the boilers using existing material handling systems.

The Ely plant is a dedicated straw fired power plant of 38 MW capacity where square "Heston" bales are fed directly into the boiler. Wheat straw is the preferred fuel. However, barley and oil seed rape straw is also accepted and blended with wheat straw to produce an acceptable feedstock. A moisture level of 14% is desired however a moisture level of up to 25% is accepted. The only criteria for acceptance, beyond moisture content, is good bale integrity. Bale integrity is important as the ability of that bale to be handled and stacked is paramount. Therefor it is quite acceptable for the bales to be stored, uncovered, in the fields throughout the year. The Ely plant consumes 600t/day or 220,000t/year and if you accept Ely's quoted capacity of 38 MW then they are producing 1.52 MWhr/t of straw. The price of straw for the 2013 season was AU$72/t baled at the farm gate which then equates to a fuel cost to Ely of AU¢4.73/kWhr.

Studies conducted by Ely suggest that approximately 30% of the crop biomass is removed through the straw baling process and the nutrients removed and exported as part of the straw equates to AU$9.60/t. Tim Pratt of Farm Energy Centre describes the burning of straw as an exciting prospect but it is not without its issues which can be summarized as follows:

- Handling and storage of a bulky and low density product,
- Transport cost,
- Pre-chopping and teasing out prior to feeding into the boiler,
- The low ash melting temperature of straw (~800^{o}C) as opposed to wood (1,100^{o}C) and

- The corrosive nature of the clinker and ash due to potassium, sodium and chloride.

Mr. Pratt also suggests that an industry accepted value for good gross boiler electrical efficiency would be between 20% and 22%. Gross boiler electrical efficiency can be described as follows:

Gross Fuel Value	=	Inherent gross calorific value of fuel,
Net Fuel Value	=	Gross Fuel Value less Flu heat loss,
Electrical Value	=	Net Fuel Value x Boiler efficiency.

Hence gross boiler electrical efficiency is,

= Electrical Value / Gross Fuel Value %

The Irish Governments Agriculture and Food Development Authorities Teagasc publication "Straw for Energy" 2010 gives the following energy values for various types of straw.

Table 10: Energy values of straw at 15% moisture			
	Calorific Value (MJ/kg)	Energy (kWhr/t)	Ash Content (%)
Wheat Straw	14.4	4,032	5.7
Barley Straw	14.7	4,116	4.8
Rape Straw	14.3	4,004	6.2
Meadow Hay	14.3	4,004	7.1

Source: (Teagasc, Agriculture and Food Development Authority, 2010)

Andrew Baada operates a 52,800 m^2greenhouse near Hull in Yorkshire which utilises a 2.5 MW straw fired boiler to provide heating for the greenhouse operation. The boiler generally operates from January through May and will consume 2,500 t of straw during this period. The straw fired boiler provides up to 80% of the greenhouses heating requirements with the remaining demand being supplied from a natural gas fired boiler.

The straw fired boiler system is highly automated and computer controlled where straw is fed into the boiler on an as required demand basis. One day’s requirement of straw can be loaded onto the straw feed table which then feeds the straw into a shredder which teases the straw from the bale and cuts it into a size suitable for feeding into the boiler. On average the system burns one 650kg "Heston" bale per hour.

Figure 9: Danstocker boiler and straw bale feed table

Mr. Baada uses a Danstocker solid fuel boiler which is fitted with pneumatic "shock blasters" which keep the boiler clean of clinker and which allows the successful use of cereal straw as a fuel. On average 5-6% ash is produced from the boiler. This ash is collected and spread back onto the farm thereby retaining nutrients removed from the field through straw collection.

Mr. Baada provided the following actual energy values achieved through his boiler for miscanthus and wheat with various moisture contents. Note, net calorific value is the gross fuel value less boiler flu losses and Mr. Baada is producing heat energy and not electrical energy.

Table 10: Energy values of miscanthus and wheat at various moisture levels

Moist (%)	Wheat Straw Net CV (MWhr/t)	Miscanthus Net CV (MWhr/t)
0	4.6	5.0
5	4.3	4.7
10	4.1	4.4
15	3.8	4.1
20	3.5	3.9
25	3.3	3.6
30	3.0	3.3

35	2.7	3.0
40	2.5	2.7
45	2.2	2.4
50	2.0	2.2

Source:(Baada, 2013)

3.3 Bio Char

Bio Char is potentially an exciting development in agriculture that was first developed by the Amazonian Indians thousands of years ago. The Amazonian Indians dug large pits into which they would place all types of organic material, when the pit was full they would then cover and seal the pit, preventing the ingress of oxygen, and then ignite it to create their Bio char. They would then use this Bio char to ameliorate the highly acidic and very low fertility soils typical of the Amazon Basin.

Bio Char is essentially the charcoaling of organic material via a process called pyrolysis that exposes the organic material to high heat in a low oxygen environment resulting in the production of syngas, bio oil and bio char components. The relative amounts of each component produced are determined by the heat applied during the pyrolysis process. The higher the temperature the greater the proportions of bio gas and bio oil and the less solid bio char and the reverse is true for the lower the temperature during pyrolysis. The interest in Bio Char is threefold:

- Firstly, all three components of the pyrolysis process are combustible and therefor are potentially bio fuels,
- Secondly, there is great interest in the Bio Char fraction as a soil ameliorant and
- Finally, the Bio Char fraction is a highly stable form of carbon that may be well suited to sequestration in the soil.

One of the primary difficulties with using agricultural residues as a bio-fuel source is their relatively low physical and energy densities. The pyrolysis process has the potential to address this. In her Doctoral thesis, (Abdulla, 2010) shows that Oil Mallee with an untreated energy density of 10 GJ/t, can be converted to bio-char with an energy density of approximately 28 GJ/t. Collie coal has an energy density of ~26 GJ/t. Untreated bio char still has a relatively low volumetric energy density of ~8 GJ/m^3 however after grinding this density can be increased to ~19 GJ/m^3 which compares very favorably with Collie coal which has volumetric energy density of ~17 GJ/m^3.

The use of bio char as a soil ameliorant is presently the subject of much research globally but thus far there is no definitive conclusion as to its value. Many studies have shown significant agronomic benefits however a smaller number of studies have shown no benefit or even adverse effects (Krull, Sohi, Lopez-Capel, & Bol, 2009). The nutritive value of the bio char is greatly related to the original feedstock however generally it can be said that Bio Char has the following properties when added to the soil:

- Retaining nutrients and cation exchange capacity,
- Reducing soil acidity,
- Decreased uptake of soil toxins,
- Improved soil structure,
- Improved nutrient use efficiency,
- Improved water holding capacity and
- Decreased release of potent greenhouse gases including methane (CH_4) and nitrous oxide (N_2O).

Care does need to be taken when considering bio-char as a soil ameliorant as some studies have shown a negative effect on yield when it is used. Pot trials conducted by the UWA suggest that biochar when added to some soils may actually tie up nitrogen and also result in reduced microbial activity both of which resulted in reduced yields (Lee, 2010).

(Finch, 2013) and (Cross, 2013) of the U.K. Bio char Research Centre (UKBRC) located in the University of Edinburgh are studying the effects of bio char on soil and have developed a toolkit to quantify the value of different bio chars as well as supplying researchers globally with research grade bio char. Research grade bio char is bio char that is predictably consistent in its chemical characteristics and manufacture such that results from different experiments using this product can be compared accurately. The toolkit developed by the UKBRC is used to rapidly assess the function of different bio chars using the following parameters:

- Labile carbon,
- Stable carbon,
- Priming potential,

- Nutrient value and
- Soil structural benefits.

Bio char produced through pyrolysis is an extremely stable form of carbon that can remain inert for hundreds if not thousands of years. As the material being used to manufacture bio char was originally organic and therefor part of the photosynthesis cycle any carbon that is locked up as bio char is no longer available to enter the atmosphere as a greenhouse gas (Krull, Sohi, Lopez-Capel, & Bol, 2009). This form of sequestration is easily auditable as the carbon production can be weighed and analysed. Carbon in bio char is also highly inert. This compares favorably with soil sequestration of organic carbon which is difficult to measure and may easily be oxidised especially with soil cultivation.

3.4 Pelletization for feed

Perhaps the easiest and most logical use for harvest residues would be to incorporate it into a feed ration through a pelleting plant. If the logistical issues of handling and transport could be overcome, then both chaff and chaff and straw could form a valuable component of a livestock feed ration. Due to the difficult physical nature of chaff, but also of baled straw, the closer to the source of the harvest residue the potential plant was located the better, thereby reducing as much as possible the cost of transport.

Mr. Andrew Foster, Mill Manager, Primary Diets, Yorkshire, U.K. described the pelleting process as follows:

- Raw ingredients are gathered and pre-ground if required,
- Ingredients enter a mixer to be thoroughly mixed,
- Ingredients are ground again; even particle size is critical for a good pellet,
- Ingredients enter a steam conditioner which raises the temperature and adds moisture,
- Ingredients enter the pellet press,
- Pellets are fed into a cooler to lower their temperature to ambient levels and
- Pellets are then stored prior to distribution.

Mr. Foster's plant manufactures 40,000 tonnes per annum of pellets for use as piglet starter feed. This is achieved via two, 2.5t/hr pelleting lines, with direct manufacturing costs being approximately AU$64/t. The ingredients used are constantly assessed and varied to provide the lowest cost feedstock without jeopardizing the final pellet quality. A piglet starter ration is different from a compound ration. The ration is based on a cereal being wheat, barley or maize. Protein is sourced from either soy bean meal, fish meal or soy oil and milk products such as whey powder and skim milk powder complete the mix. The use of milk products is useful as they have a binding effect. However, temperature has to be kept low to prevent burning of the milk proteins which causes an unpleasant taste.

Figure 10: Pellet press and pellets

Wheat is a very good grain for producing high quality finishing pellets, however barley is more problematic as it does not bind as well, making the finished pellet more fragile. Oil is critical for producing pellets, with 6-8% of oil by weight being required to produce a high quality finished product (Foster, 2013).

Mr. Andrew Sadler is the plant manager of ABN Feed Mills, Northallerton, UK. Mr. Sadler's plant produces compound pellets via two pelleting lines, one 17 t/hr line producing a ration for broiler chickens and a second 15 t/hr line producing a ration for pigs. Due to the higher throughput of this plant direct manufacturing costs are approximately AU$16-24/t. Due to this plant producing a compound pellet, whose ingredients typically comprise cereal chaff and straw plus various grains, they are able to press at a higher temperature. Pellets typically fall from the press at 81°C which effectively pasteurizes the pellet making it safe from salmonella.

Mr. Sadler describes the benefits of pelleting and conditioning as follows:

- Pelleting;
    - Increases bulk density,
    - Prevents de-mixing of ingredients,
    - Increases feed intake.
- Steam Conditioning;
    - Improves digestibility and
    - Kills bacteria such as salmonella (Sadler, 2013).

The question is, can crop residues be used to make a viable feed pellet? Table 11, below, describes the nutrition value of many types of chaff and chaff and straw.

Table 11: Fodder value of chaff and straw								
Sample	DM %	Prot %	Energy MJ/kg	Ca %	P %	Mg %	ADF* %	TDN** %
Wheat Chaff	91.1	4.6	8.3	0.24	0.08	0.12	51.5	43.6
Wheat Chaff and Straw	86.1	4.0	7.4	0.25	0.12	0.09	51.3	39.7
Barley Chaff	88.8	6.5	9.2	0.52	0.13	0.17	42.8	53.0
Barley chaff and Straw	88.5	5.0	8.3	0.45	0.11	0.15	49.6	45.6
Oat Chaff	87.4	7.2	10.1	0.71	0.14	0.23	42.6	53.1
Oat Chaff and Straw	84.4	5.1	8.3	0.39	0.1	0.15	50.1	45.1
Canola Chaff	88.6	5.9	7.4	1.45	0.12	0.33	56	38.5
Pea Chaff	79.4	9.2	7.4	1.76	0.13	0.35	46.1	42.0
Pea Chaff and Straw	89.1	7.0	7.4	1.56	0.11	0.27	54.8	40.1

ADF – Acid Detergent Fibre.

*****TDN – Total Digestible Nutrients***

Source: (Stauss, 2008)

If we use the example of wheat chaff as a feed stock for the production of a pelletized ration, we can see from Table 11 that the wheat chaff provides 4.6% protein and 8.3 MJ/kg DM of energy. If the pellet being produced was intended for finishing sheep, then a likely requirement for protein would be 15% and energy 12 MJ/kg DM. The wheat chaff is two thirds of the way there, with respect to energy, but only one third of the way there for protein. It would follow that the wheat chaff would need to be augmented with other, high protein, feed stocks to produce a suitable ration. Table 12 below describes the nutritional value of various feed grains.

Table 12: Nutritional value of various feed grains			
Grain	Dry Matter (%)	Met Energy (MJ/kg)	Protein (%)
Wheat	91	12.9	11.5
Barley	91	11.9	11.0
Lupins	92	14.0	38.0
Peas	91	13.0	25.0
Vetch	91	12.8	29.0

Source: (Kroker & Watt, 2001)

Therefore, from Table 12 we can see that a ration made up of 68% wheat chaff (4.6% protein, 8.3MJ/kg energy) combined with 32% lupins (38% protein, 14MJ/kg energy) would make a feed pellet that has 15.2% protein and 10.1 MJ/kg energy. This simple mix meets the requirements for protein but falls a little short on the energy front. Obviously, the design of a complete feed ration is more complex than the above simple example and would probably utilize many other feed stocks, including oil seed meals and perhaps molasses to remedy any energy deficiency. However, it does demonstrate that the manufacture of high quality feed pellets from harvest residue is entirely feasible. The exciting part of the above example is that 68% of a high-quality feed ration could potentially just be lying out there in the paddock, waiting to be picked up.

3.5 Material manufacture

An exciting potential use for cereal residues is as a fibre source for material manufacture from paper and cardboard to chip board or particle board. Styrofoam will soon be banned in the United States of America (Lewis, 2013) which will open an enormous market for disposable food containers. Harvest residues can be processed through a pulping and refining mill which extracts the fibers for paper and cardboard as well as refining the liquor for the production of highly valuable Glycols. There is also growing concern in the United States of America about the levels of Formaldehyde in particle board (Knott, 2013), which has the potential to open another large market for alternative fibres.

Mark Lewis, Director of Paper Science Centre, Washington University, is studying the suitability and use of cereal straw as potential feedstock for the production of disposable food containers. Dr. William McKean, Professor Paper Science Centre, University of Washington, is studying the production of Glycols from cereal straw.

Messrs. Lewis and McKean are developing a proposal for a commercial scale pulping and refining plant to be located at the wheat growing area of south eastern Washington State. Their proposal is summarized below (Lewis, 2013) (McKean, 2013).

Mr. Don Knott, Ontario Canada, is a farmer and member of the Ontario Bio Mass Producers Co-Op. Mr. Knott grows Switchgrass, a perennial bunch grass native to North America, on 25% of his property for fibre production. The Ontario Bio Mass Producers Co-Op is a group dedicated to the growing and marketing of fibre crops. So far they have developed a total of 23 actual and potential markets for fibre crops. Mr. Knott sells his Switchgrass in “Heston Bales” to dairies in the USA and to the mushroom industry as substrate for compost.

Mr. Knott is also in a partnership that is developing an alternative to traditional particle board utilizing finely ground Switchgrass combined with a resin derived from corn, soy and recycled plastic. Mr. Knott reports that formaldehyde, a primary constituent of traditional particle board, will soon be banned in Canada and the USA potentially providing a huge market for his development.

4. Chaff and straw handling systems

The greatest difficulty when dealing with chaff and or straw is the low density and low value of the product and the consequent expense involved with the logistics of handling and transporting of the product. Two popular systems for capturing harvest residue during the harvesting process are the collection of the chaff portion only using a chaff cart/wagon or the complete capture of all the harvest residue, chaff and straw, via baling.

4.1 Baling

Baling of harvest residue can be achieved in two ways, firstly the residue may be windrowed on the ground behind the harvester and then baled in a secondary process at a later time. Or secondly the residue can be baled directly behind the harvester in a single pass operation. The process of baling harvest residue directly behind the harvester is known as "Combaling" and requires some modifications to both the harvester and the baler. The system developed in Western Australia and used widely in the Kennewick area of south eastern Washington involves adding a conveyor system to the rear of the harvester to capture both the chaff and straw which is then transported to a conventional square bale or "Heston" type baler. The baler has had the conventional pick up front removed, which is normally used for the picking up of windrows, and adapted to allow the delivery of the chaff and straw via the conveyor system.

Figure 11: Combaling and stacking bales

John McCaw,Waitsburgh, Washington, uses the combaling system in his12,000Ha per year custom harvesting business. Mr. McCaw reports that the majority of the straw that he bales is sold to feedlots as a ration and is valued at approximately AU$62/t in field. Straw yields vary with the crop being harvested, a 6.7t/ha winter wheat crop can yield anywhere between 5-10 t/ha of straw (McCaw, 2013)

Curtis Coombs and Jason Lynch, Walla Walla, Washington, operate their own farming business as well as contract harvesting including combaling. Mr. Coombs reports that farmers are very keen to have their crops combaled as the straw is cut very low and the baling process removes all crop residues, which makes the following planting or ploughing process trouble free,due to the improved trash flow. Mr. Coombs charges only the cost of fuel and takes the straw as payment for contract harvesting. Straw is worth approximately AU$53/t and sold to either feedlots, mushroom farms in Canada or even exported to China. Mr. Coombs uses Massey Fergusson 2170 balers coupled to his harvesters; the balers are hydraulically driven, supplied from the harvester and requiring approximately 120 Hp. The balers cost AU$160,000 and the conversion costsAU$40,000 (Coombs, 2013) (Lynch, 2013).

After the bales of straw have been placed in the field by the combaler they need to be retrieved and stacked in haystacks ready for transport. The process of bale collection and stacking is achieved very efficiently using a variety of "bale buggies". The Mil-Stak bale buggy is indicative of the machine used and can collect ten square bales "on the run" using an automated hydraulic grab system. The bale buggy then returns to the haystack, reverses up to the haystack and then the trailer tips up and all ten bales are in place in a single operation.

The great advantages of the combaling system is that it collects all residues from the harvesting process in a single pass system and that the residue is collected in a conventional bale which is ideally suited to handling and transport using readily available machines and equipment.

The disadvantages of the combaling system are that because it does collect the entire harvest residue there is a large volume of low density material to handle, there may not be a ready market for baled straw, the power requirements to run the baler are relatively high and the cost of equipment required for the operation is expensive.

4.2 Chaff carts

Chaff carts are a concept originally developed in Saskatchewan, Canada, by the Redekop manufacturing company and subsequently introduced into Australia in the 1980s. Chaff carts are a fairly simple concept where the chaff from a harvester is collected as it falls from the top sieve and is either blown or transported via a conveyor belt into a large wagon trailed behind the harvester. The wagon is unloaded intermittently and the chaff previously collected is deposited in piles throughout the paddock. These piles are then burnt, left for livestock to graze or picked up and transported for other purposes.

Figure 11: Chaff carts and compacting truck trailer

David Campbell, Scadden, Western Australia, harvests using chaff carts and either burns the piles or collects them for his compost operation. Mr. Campbell tows a 39m^3 Riteway chaff cart behind his harvester which utilizes the conveyor belt system to transport the chaff, and a portion of straw, into the cart. To collect the chaff Mr. Campbell utilizes a 59m^3 compacting truck trailer, loaded with a front-end loader, which can compact up to four piles of chaff, approximately 160m^3, and transport it to his composting operation. Mr. Campbell reports that a chaff cart equivalent to his costs approximately AUS100,000 fully installed and ready to operate (Campbell, 2013).

The advantages of chaff carts are their simplicity, light weight and their relatively low cost.

The disadvantage of chaff carts is that they are collecting and depositing loose chaff in discreet heaps all over the harvested paddock. Chaff is an extremely low density product which is logistically difficult and expensive to re-handle, if that is the objective, or it must be burnt in-situ which has its own expense and inherent dangers.

Conclusions

It is clear weed resistance to many common and important farm herbicides is a real and increasing problem within the Western Australian grain farming regions and in particular, the Esperance Port Zone. The development of weed resistance is further exacerbated within the Esperance Port Zone by the increasing proportion of arable land being planted to grain crops, at the expense of pasture, the all but exclusive use of minimum tillage practices and the heavy reliance on chemical weed control that is required within that system.

To combat the emergence of weed resistance farmers are trying to incorporate non-chemical weed control practices, commonly known as Integrated Weed Management (IWM), to mitigate the development of weed resistance. The practice of collecting chaff or chaff and straw during the harvesting process is a common form of IWM with the harvest residue being collected in either windrows, chaff heaps or baled straw and then typically being burnt.

The purpose of this report was to look for new or innovative means of weed control during the harvest period, either denaturing weed seeds as they pass through the harvester, or recovering the chaff or chaff and straw and finding a commercial purpose for it.

Perhaps the most elegant and ultimately cost effective means of achieving weed control during the harvesting process would be to denature the weed seeds as they pass through the harvester. This would achieve the goal of weed control in a single pass with no further handling of problematic materials and return all organic matter to the field thereby preserving significant nutrients within the soil. There is great potential for the use of microwave energy to achieve this although the concept is in the embryonic stages of development. The great advantages of this idea are that there would be minimal mechanical contact with the material being treated and the great possibility that it could be incorporated within the harvester itself.

If there was no other option but to collect the harvest residue, then the option most likely to be economically viable would be to collect and dump chaff from the harvester using a chaff cart and then collect those chaff dumps at a later stage for processing into pellets for animal consumption. This option would be most likely to prove the least capital intensive and technically difficult and would fit most comfortably within the enterprises of Western Australian farmers.

The production of electrical energy from harvest residues is a most exciting concept that is widely used in the UK and Europe. It would seem that the use of anaerobic digestion would struggle to be economically viable as harvest residue is more suited to direct combustion. Direct combustion of harvest residue to produce stream to drive a turbine to produce electricity would seem the most economic means of producing electricity. Although the economics of bio-energy electrical generation within the Esperance Port Zone at this stage appears marginal it does demand further investigation.

Bio char is an ancient technology that has exciting modern day potential. Bio char is commonly produced for the char (carbon) portion, with the bio gas and bio oil fractions being used primarily to fuel the process with no energy being exported. There is still much conjecture about the value of bio- char as a soil ameliorant and therefore its value.

Finally, there is much research being conducted into the use of harvest residues in the production of paper, cardboard, particle boards and further refining into valuable glycols. These are very high value industries however they also require the greatest amount of capital investment and technical expertise.

Recommendations

To succeed in the battle against weed resistance to agricultural chemicals the Australian cropping industry needs to;

- **Do something:** the adaptation of Integrated Weed Management techniques, regardless of what they are, is essential.

- **Pursue seed denaturing.** Integrating some means of seed denaturing, be it either mechanical or using microwaves, into the harvesting process will provide a very high level of weed control.

- **Weed seed collection.** Until seed denaturing becomes more viable then the best option is to collect weed seeds during the harvesting process for further treatment or use.

- **Expand crop rotations.** The search for profitable new markets and crops to further expand the currently available rotation needs to be continuous. This will allow farmers to use a wider suite of chemicals and techniques to control weeds.

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Plain English Compendium Summary

Project Title:	Name of project
Nuffield Australia Project No.:	1203
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Objectives	The objective of this research was to investigate the ways, means and economics of non-chemical weed control in broad scale farming to prevent the occurrence of chemical herbicide resistance.
Background	Modern Australian farming techniques rely heavily on the use of chemical herbicides for the control of weeds within the crop. The more a weed is exposed to that herbicide the greater the probability that that weed will develop resistance to the chemical. Additional non-chemical means of weed control need to be incorporated into the farming system to delay or prevent the occurrence of weed resistance to common, cheap and effective farm chemicals.
Research	This research focused on the collection of weed seeds during the harvesting process and the subsequent removal or destruction of those seeds. Thereby lowering the weed burden through non-chemical means. Research was conducted in Australia, the United Kingdom, Belgium, Canada and the United States.
Outcomes	Integrated weed management during the harvest process is still in its infancy within Australia and globally although there are many exciting possibilities. Further development is required and is being pursued however until then farmers need to continue non chemical weed management to preserve for as long as possible the existing chemical herbicides.