Comparative Costs of Harvesting Irregular and Regular Mixed Conifer Stands at Stourhead (Western) Estate

A dissertation submitted in partial fulfilment of the requirements for the degree of Master of Science (MSc) in Forestry of Bangor University

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Abstract

Stourhead (Western) Estate in South Western England provided a unique opportunity to evaluate the comparative productivity and therefore costs of harvesting for differing stand structures and harvesting techniques within the same geographic setting, during the same time period and with the same equipment and operators. Four study areas were chosen: the Slope Tract (up to 25°) of Douglas fir moving toward an irregular structure by the selection system, which required motor manual felling downhill to the reach of harvester access from a forest road; the Irregular Tract of mixed conifer species with well-developed irregular structure, which required elements of motor manual felling and buttress trimming owing to timber size, but otherwise mainly mechanical harvesting; the Winch Tract of moderately-sized Western hemlock in the early stages of management toward an irregular structure, which required motor manual felling and whole tree recovery by winch prior to harvester processing; and the Regular Tract of plantation Douglas fir at third thinning stage, which was fully harvested by harvester and forwarder.

Work studies were done at each site for all harvesting methods and outputs generated for delay free and total productivities and costs for each method along with an aggregated cost per unit volume for each site. Regression equations were developed with focus on the harvester results and particularly those at the Irregular Tract. A further objective of the research was to develop regression equations for that tract which might be used alongside growth models in future economic projections for the stand in which the Irregular Tract was located.

Harvester delay free productivity results were: Slope Tract – 20.4 m³/hour, mean stem of 1.8 m³; Irregular Tract – 20.2 m³/hour, mean stem 1.0 m³; Winch Tract – 17.1 m³/hour, mean stem 0.7 m³; and Regular Tract – 8.6 m³/hour, mean stem of 0.2 m³. Harvesting costs (delay free) took account of all harvesting means employed for a particular study area and were: Slope Tract - £13.50/m³; Irregular Tract - £15.00/m³; Winch Tract - £26.00; and Regular Tract - £29.00 all rounded to the nearest £0.50. The impact of stem size was apparent in all the above results and the regression equations as well.
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David Pengelly and Andy Poore provided access to mensuration data which gave insights to the overall forest at Stourhead which facilitated the choice of work study plots to achieve the objective of comparability of the different harvesting conditions, from both silvicultural and operational perspectives. My thanks go to Christopher Guest for assisting in the marking of the stands and some of the product measurement.

Special thanks go to several persons who were very helpful in advising on aspects of the research based on their direct experience of similar studies: Martin Price of Forest Research for his advice on the field conduct of harvesting studies; Lars Eliasson of Skogforsk for practical advice on work study design and data capture and Dr Andreas Forbrig of KWF, not only for provision of insight into the harvesting machinery cost studies of KWF, but also patiently answering my many questions on those and filling the gap where literal German/English language translations did not work.

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1 Introduction

1.0 Background to the research

Regular forests, clear-fell harvested on a rotation, have dominated British forestry since early in the last century. However, in the UK and worldwide, there is an ongoing debate on whether changing social views, climate change, onslaught of pests and diseases and security of future productivity might demand changes in silvicultural practices (Diaci et al, 2011). Stourhead (Western) Estate was an early mover in transforming areas of the forest away from clear-fell and toward continuous cover and alternative silvicultural practices. That transformation was aided by the long-established practice, for aesthetic reasons, of small-scale clear-fells followed by replanting of a variety of softwood species. However, more than two decades ago, the forest owners and managers purposefully began moving large areas of the forest toward an irregular structure (Poore, 2007). So today there are areas of the forest which have largely achieved an irregular structure in the classic sense – a variety of ages and sizes (Schütz, 1997) along with a still-developing mixture of species. At the same time, other areas of the forest were previously managed under a regular silvicultural system and are at an early stage of movement toward irregular silviculture.

1.1 Harvesting methods and costs

Along with changing silvicultural practices, harvesting methods have also evolved at Stourhead. With the development of harvesters and forwarders, forest road and rack systems have been and are being established to facilitate the efficient use of that equipment and minimize soil structure damage in the forest. Hand felling and winch tractor extraction, while still necessary in part, have largely been replaced by full mechanisation. For some time, the forest owners and managers have been debating the cost implications for harvesting under the varying circumstances at Stourhead, with one of the owners musing that perhaps the irregular parts of the forest might incur greater harvesting costs, perhaps 20% greater than those in the regular compartments. The desire to better understand harvesting costs arises not just from consideration of profitability, but also recognition that harvesting
companies must earn an acceptable return to remain viable. From a broader perspective, better knowledge of costs of harvesting stands managed under alternatives to regular silviculture appears to be an important factor around which too little is known today. Knoke (2012) did a literature review to highlight the various approaches to analysing the economics of alternatives to even-aged silviculture, 'Rotation Forest Management', in his terminology. His conclusions suggested a bright economic future for continuous cover forestry (CCF) in the boreal and temperate zones – and a desire to see more research done. Puettmann et al (2015) recently explored why, in the face of a growing body of evidence, alternatives to even-aged management have not been more widely adopted. The expert contributors to that publication identified a range of factors, among those were harvesting issues. Operational and cost implications outside the realm of clear-fells were identified as areas lacking in knowledge and understanding thereby leading to risk aversion in adoption.

### 1.2 Harvesting cost study approach

In consultation with the forest manager, David Pengelly, and Andy Poore, a variety of compartments were reviewed for inclusion in an assessment of costs of harvesting which would demonstrate the range of harvesting scenarios being experienced. Stourhead presented a unique setting with its variety of forest types ranging from regular through to well-developed irregular, a variety of species and differing terrain as well. That meant the study had potential to develop comparable data for different situations completely within its scope.

Classic work study methods, similar to those used by the former dedicated work study branch of the Forestry Commission (Forestry Commission, 1978) were employed to derive harvesting productivity (m$^3$/hr). Work study was preceded by overall site evaluation, e.g. terrain, stand characterisation and marking of timber to be felled followed by mensuration of products as required. Mensuration again used classic techniques as defined in texts by Philip (1994), Husch et al (2003) and Matthews & Mackie (2006). Finally cost assessment (£/m$^3$) was grounded in the
machinery cost evaluations of KWF (Forbrig & Büttner, 2013) adjusted for exchange rate.

1.3 Primary objective of the research

The primary objective of the research was to quantify harvesting productivity for the chosen study areas and convert those productivities to overall cost per cubic metre harvested in each study area. Those cost findings would be supported by descriptive data which would facilitate use of the findings in future harvest areas at Stourhead as well as in economic projections for the forest.

1.4 Limitations

The nature of on-the-ground work studies is such that the mensuration and time study data collection consumes a great deal of time as does the subsequent data organisation, verification and processing of results. The field work alone for this research consumed nearly thirty days. Hence, from a practical perspective, one is limited in the size/volume of harvesting study areas. That has to be considered when developing/using regression equations or extending results to other situations. However, it is believed the rigor of the data collection and analysis in this research was and is as good as it could have been and while one should be cautious to interpret limited statistics too literally, the comparative results between the study areas are believed to demonstrate real differences.

The same operators and harvesting equipment were used for all study sites. The former was an advantage since regardless the performance level of the operators, they were the same in each case. With regard to harvester and forwarder, some may argue those could have been smaller and more manoeuvrable (and less costly) for the Regular Tract study. As a practical matter, this author did not observe a penalty with the larger equipment in the Regular Tract and it is believed using the same operators and equipment in all cases was reasonable.

Terrain and other site-specific conditions were observed to impact harvesting times. Those variables were recorded in the data compilation for each study area, but
could not be analysed as independent variables. Weather conditions were generally good and did not present as a variable in the four harvest areas.

1.5 Structure of thesis

Following this introduction, the thesis is structured in five main sections: Literature Review, Methods, Results, Discussion and Conclusion. Chapter 2, Literature Review, touches on how policy and silvicultural practice development make this study relevant, but focusses particularly on the work and cost study literature which informed this author’s work. Chapter 3, Methods, describes the research sites, selection of work study methodology and equipment, elemental designs for the work studies, measurement techniques and the source of machinery operating cost data. Chapter 4, Results, records the specific characterisation of each site, ‘by method’ harvesting productivity results, aggregate and ‘by method’ cost results and notable regression results for productivity. Chapter 5, Discussion, considers the results in light of the objectives and relevant work of other researchers. Chapter 6, Conclusions, sets out observations and final conclusions on the results.

2 Literature Review

2.0 Policy and silvicultural practice

Interest in alternatives to even-aged, mono-species forests, typically harvested by clear-fell, has been growing in the UK (Helliwell & Wilson, 2012), Europe (Tahvonen, 2007; Schütz, 2011; Brang et al, 2014) and North America (Bohn & Nyland, 2006; Raymond et al, 2009; Bose et al, 2014) among other areas of the world. The 7th IUFRO International Conference on Uneven-aged Silviculture (IUFRO, 2010; Diaci et al, 2011) featured sixty presentations on different aspects of the topic.

A number of recent publications confirmed wider public and policy recognition that the dominant even-aged forestry practices of the 20th Century in the UK must adapt to changing environmental conditions and values. Research conducted for the Department for Environment Food & Rural Affairs (Eves et al, 2014) sought to understand the drivers and constraints impacting on forest owners such that policy might be designed to encourage more owners into active management for future
conditions. The ‘Climate Change Accord: a call for resilient forests, woods and trees’ of July, 2015 (Forestry Commission England, 2015) published a list of principles and statements from public, private, commercial and charity organisations setting out their intended actions to achieve more resilient forests in England. Many of those called for a move toward greater species and structural diversity, less even-aged silviculture and bringing forests back into active management. In the UK, that call was not an entirely new one. From early this century, the Forestry Commission had established CCF trial forests and the operational experiences of those were reviewed by Ireland (2006) – with no findings of insurmountable challenges. Wilson (2013) did a wider review of active alternative silvicultural systems with similar conclusions. However, over a decade after trials began, Mason (2015) observed that notwithstanding policy objectives to move to greater species and structural diversity, uptake of continuous cover forestry (CCF), as an alternative to even-aged silviculture with potential to address many of the policy objectives, was less than 10% and that technical and cultural challenges would need to be overcome to achieve wider adoption. Among those challenges were predicting costs and revenues. Mason’s view was the evidence for costs and revenues was limited to ‘some observational reports, few detailed studies’ (Mason, 2015, p.893). The need for empirical data to support dialogue and decisions on the implications for costs of moving toward different forms of silviculture seems clear in light of policy objectives and the lack of data today.

2.1 Harvesting work study

Work study techniques under-pinned the data collection for this research. The work of other researchers was reviewed not only to inform selection of the particular work study tools and work study design, but also to review post data acquisition processing and, if possible find results for use in comparison to those achieved in this research. Work study tools, design and data processing were covered by a substantial body of research. However, comparable studies were less available, which should not be surprising given the early stage of adoption of any form of alternative silviculture, particularly in softwood production forestry.
As noted in the introduction, the UK Forestry Commission had a dedicated work study branch which operated for more than two decades for the purpose of improving productivity and setting contractor productivity/pay rates. A book published near the end of the branch’s separate existence (Forestry Commission, 1978) shows how little has changed over time. The work study fundamentals were and are intuitive and appear to have been followed subsequently by the Technical Development organisation of Forest Research, e.g. (Forest Research, 1998; Forest Research, 2003; Ireland, 2008; Ireland, 2009).

Kuitto (1994) set the scene for mechanised harvesting work studies over successor decades. That study work, through Metsäteho (the Finnish research and development body owned by forestry industry organisations) was done for the primary purpose of establishing bases of payment to contractors for mechanised cutting and forest haulage. It remains unique in scale for an observational work study – 30 harvesters and forwarders on 1329 worksites with over 642,000 m³ harvested. While the results of that work have lost direct application with the passage of time, largely owing to technological development of equipment, the fundamental approach has remained applicable. That was and remains one of breaking down the work of the machinery to recognisable sub-elements, e.g. boom movement time, stem felling time, in support of satisfying particular objectives. Researchers then sought to relate physically observed and recorded time consumption to independent variables, e.g. stem size, such that a basis for productivity could be derived, explored and perhaps improved. Time productivity results could then be converted to cost productivity, e.g. monetary unit per cubic metre or tonne, based on the operating cost defined for the equipment in use.

2.1.1 Work studies comparability

A goal of most work studies is to do the work in such a way that the results can be compared to previous work. Given the many variables in harvesting operations – machinery, operator, terrain (e.g. slope, soils, ground roughness), species, product selection, harvesting methodology – just to mention a few, it should be unsurprising that comparability will at best be imperfect. As early as 1988, an IUFRO Work Study,
Payment and Labour Productivity work group was appointed to address the issue of comparability of work studies (Björheden et al, 1995). At that time, the fundamental issue was seen as classification of time: e.g. workplace time, non-workplace time, delay time, etc. Ultimately, a quite detailed nomenclature guide was published in 1995 on a ‘test’ basis. No final document can be found. Nearly two decades later, Magagnotti & Spinelli (2012), as editors for a large group of experienced researchers, lamented the drift away from common study methods and sought to harmonise work study approaches of researchers. The good practice guidelines they published are commended for their clarity, simplicity – and recognition that harmonisation is not standardisation. Their conclusion that comparability of work study research fundamentally depends on ability to understand the detail of any study before attempting any comparison seems unarguable.

2.1.2 Work study tools

While the principles of work study have not changed, the technology has. Current techniques include: empirical observation studies with the modern equivalent of the stopwatch and clipboard – a handheld computer or video recorder; post-harvest, follow-up studies using harvesting machine on board computer data, e.g. Erikson & Lindroos (2015), and trials of artificial neural network approaches e.g. Bayati & Najafi (2015). Literature was reviewed to understand the attributes of the various approaches and guide selection of an appropriate technique for the current harvesting study.

Institute of Sweden, also used the Haglöf solution (Eliasson, 2016). The common elements of the data recorder approaches are rugged, button-programmable, long battery life, handheld computers running proprietary, customisable software. This technical solution preserves the direct and instant interaction between a skilled researcher and the separate, observable work elements and offers a field hardy platform, though at a substantial cost of over EUR 3000 for the Haglöf solution (Wikner, 2016).

Some work study practitioners have adopted the video camera as the primary field observation tool, supported by in-office processing of the video through a work study package – a natural progression from the handheld data logger. Nurminen et al (2006), Nakagawa et al (2007), Coup (2009), Klepac & Rummer (2012) and Strandgard et al (2013) all used this approach. Coup (2009) and Klepac (2016) processed the video with commercial time study packages which are widely available, Laubrass UmtPlus® (2017) and Timer Pro™ Professional (2016) respectively.

As observed by Strandgard et al (2013) and experienced by this author, conventional time studies of harvesting operations require a great deal of field work and as a result are costly, which can limit the extent of study. These factors, along with increasingly sophisticated on board computers have created opportunity to conduct some harvesting studies largely from analysis of the captured machine data. For the Nordic countries, StanForD 2010, the successor to the original 1987 version, sets a standard for operating software used by all the major harvester and forwarder manufacturers, including John Deere, Komatsu, Rottne, Log Max and others (Skogforsk, 2013). StanForD is gaining wider acceptance over time, e.g. John Deere (2018). The software captures data at a granularity that facilitates many aspects of work study, if the software is properly set up and used by a trained harvester operator.

Spinelli et al (2010) developed general models for Italian harvesters by extracting the machine data associated with 38 time studies previously done by the same authors in the traditional way – Husky Hunter field computers with time-study
software. The authors were satisfied that the productivity models generated from machine data generated valid models as proven by comparison with actual values from a dataset reserved from the original 38 studies for that purpose. However, it was acknowledged that such an approach as they took tends to even out all factors except tree size, thereby qualifying the use to which the results might be put.

Strandgard et al (2013) evaluated the results of harvester productivity derived from StanForD files versus productivity derived for the same trees from traditional work study techniques using a Windows CE PDA with Timer Pro™ Professional software. While no significant differences were found, the software files results generally exhibited a poorer fit than the traditional work study results. The authors noted the time and cost savings of automated data collection and elimination of the “Hawthorne effect” possibly caused by physical presence of the observer in a time study. However, they recognised that StanForD 2010, necessary for study at time element level, would take some time to become integrated in machinery, and even then they suggested compliance with the standard among machinery manufacturers was variable, hence complicating comparison studies. Finally, some aspects of productivity analyses do not lend themselves to machine data capture, e.g. site ground conditions, slope, undergrowth and stem form. However, their work did strongly suggest that on board data computer files could yield productivity calculations useful for production planning and harvester performance improvement assessment.

Palander et al (2013) recognised that analysis of automatically recorded data can be problematic where work phases overlap or do not follow the expected sequence. Data needed to be manually checked for unplanned events such as e.g. multiple felling cuts or extra processing cuts. At the same time, the work rates of harvesting machinery had increased to the point where manual time studies were challenging. Palander et al (2013) attempted to address these conflicts by building a model based on principal component analysis and combined automatically and manually recorded data. The authors saw potential in this approach, particularly for machinery designers or researchers interested in finer disaggregation of the overall work cycle than is humanly possible by conventional time study.
Eriksson and Lindroos (2014) demonstrated the value of productivity analysis on large datasets routinely recorded by harvesters and forwarders working in thinnings and final fellings in northern Sweden. This stand level analysis, rather than tree level as more commonly done, demonstrated mean tree size as the most significant influence on productivity though a variety of other influencers were identified including terrain, understory, product assortment and land ownership (private versus industrial). An important finding though was that productivity had about doubled since the work of Kuitto et al (1994) thereby establishing the impact of technological development on harvesting study results. The Eriksson and Lindroos approach demonstrably offers opportunity to harvesting companies to monitor productivity in pursuit of improvement, and, importantly, more accurate production planning. However, they noted the limitations imposed by inability to achieve quality control on the data and overlay the power of human observation of the operation.

Overall, the literature suggested the choice of time study approach to a large degree depends on the research/operational questions to be answered, the form and quantity of pre-existing data and the cost/practicality of field work.

2.2 Costs of harvesting operations

As briefly mentioned in 2.1, the results of work study, nominally rate at which work is done, e.g. volume harvested/hour, can be converted to unit cost based on the hourly operating rate of harvesting machinery. Productivity is arguably reflective of cost; however, ultimately the forest owner needs to understand the cost of harvesting, particularly for roadside sales. As well, the forestry contractor, if paid on a tonne or volume basis must understand the unit cost.

It is understandable that the majority of work studies reviewed, e.g. Nurminen et al (2006), Nakagawa et al (2007), Eriksson & Lindroos (2014) and Palander et al (2013) did not include cost data since most work studies appear to be concerned primarily with productivity measures and dependencies and/or ways to improve the methodology of work study in harvesting operations. Further while harvesting
productivity depends on many factors, so too do costs vary across locations, time and currency – adding another level of complexity to output data.

Targeted costs studies added some insight. Holzleitner et al (2011) used machine-captured data to evaluate variable costs and utilisation over a four year period for a fleet of Austrian federal state forest harvesting equipment. Occasionally, time study researchers do publish cost data owing to one or more of their study objectives, e.g. Bacher (2003), Ireland (2008, 2009) and Jonsson (2015). However, that data suffers from lack of provenance and/or passage of time. It is noted Ireland helpfully provided financial spreadsheets of his assumptions, though those appear basic in nature.

The literature suggests that Germany has historically, through its regional forestry associations, pursued data capture and analysis to aid economic assessment of forestry enterprises and setting of rates to contractors. AfL Niedersachsen e.V. (AfL, 2014), the association of forestry contractors of Lower Saxony, is known for its work in publishing a selection of productivity and contractor rate data for forestry operations in its area. However, it must be borne in mind, as apparent in the published booklet and as discussed with Hittenbeck (2016), that yearly publication is designed to serve the interests of the forestry contractors, i.e. transparency of calculations behind the data is lacking and outputs include an unidentified margin.

In March 2013, nearly forty experts from across the German government and private forestry sectors met to address what was seen as a serious decline in study of working methods, productivity and tariffs (Landesbetrieb Wald und Holz NRW, 2016). That appears to mirror results of research into the economics of forest contractors in Bavaria (Borchert & Benker, 2015). That research found aging machinery, suboptimal productivity, poor economics and (unsurprisingly) unwillingness of forestry contractors to invest in the future – and referred to similar findings across other states of Germany.

The Kuratorium für Waldarbeit und Forsttechnik eV (KWF, 2016), a not-for-profit forestry organisation located in Germany, appears though to have maintained its work on costs of harvesting, particularly those associated with harvesting
equipment. KWF periodically publishes results of its cost surveys, with a primary intent being provision of information to harvesting contractors such that they better understand the fully costed economics of their operations. The KWF data seeks to be reflective only of costs, without margins, and assumptions are clearly spelt out. Published results are available for a small fee, are well set out (though in German) and there is open access to an Excel workbook in which users are encouraged to adjust input data to their particular circumstances (Forbrig & Büttner, 2013; KWF, 2016a).

No similar organisations or data appear to exist for the UK though Forest Research has occasionally (2001 and more recently 2017) conducted surveys of forest machinery across England, Wales and Scotland (Forest Research, 2017).

2.3 Previous work studies in irregular forests

While reviewing harvesting work study literature, there were two primary goals: (1) gain an understanding of work study methodologies, i.e. how to conduct an effective harvesting study, and (2) locate previous work studies in irregular forests, or at least with aspects which might be more reflective of irregular than regular forests. The literature was rich with material to satisfy the first goal, as discussed in the preceding sections. Almost without exception those studies were conducted in regular forest structures, which was in-line with expectations at the outset.

While there were no directly relevant work studies to the irregular stand at Stourhead (Western Estate), a few studies showed promise for later comparison or further informed planning for this research. McNeel & Rutherford (1994) did an early study with harvester and forwarder in a selection forest of Douglas fir (Pseudotsuga menziesii), Ponderosa pine (Pinus ponderosa) and Grand fir (Abies grandis) in north western North America; however, average DBH (diameter at breast height) was only 26.5 cm and these were very early days of mechanised harvesting. Bacher (2003) was early in the development of larger harvesters; however, selection harvest of mixed species, larger average DBH (49 cm), use of widely-spaced (40 m) racks and mixed motor-manual and harvester working in a permanent selection forest showed promise for at least descriptive comparison
with results of this research. Mederski (2006) specifically considered productivity and costs of harvesting with and without midfield in the context of transition to continuous cover forestry (CCF). Midfield was defined by spacing racks such that boom reach could not cover the full working area, with that area to be harvested motor-manually by directionally felling within reach of the harvester. His results showed better productivity and costs with midfield (35-38 m spacing) than with the usual 18-20 m spacing, and left more growing space available in the forest. The work of Bacher and Mederski influenced planning for the harvest in the Great Combe irregular tract at Stourhead (Western Estate).

No harvesting studies in irregular forests were found for the UK. However, in anticipation of greater uptake of CCF in the future, partly driven by public policy, several harvesting studies have been done in forests in transition to CCF, all with sponsorship and/or direct involvement of the UK Forestry Commission. Price, M. (2007) conducted his PhD thesis on harvesting productivity under different thinning approaches in the earlier phases of conversion of Sitka spruce forests to CCF at Coed Trallwm in Wales, a site being used by the Forestry Commission to assess operational issues of a move toward CCF. Ireland (2008) did a time study in 2007 of a shelterwood thinning in Clocaenog Forest in North Wales. Advanced regeneration and a mature over storey of Sitka spruce were present with the harvest intended to remove about half the remaining crop. Mean DBH of 42 cm and mean stem volume of 1.78 m³ made that a highly productive harvest and also demonstrated the presence of regeneration and remaining over story were manageable for the harvesters. A small time penalty of 3% was attributed to the dense natural regeneration. Later in 2008, Ireland & Kerr (2008) followed up on the shelterwood thinning experience by considering options to improve harvester head visibility when working in dense regeneration, a natural result of significant opening up of a mature Sitka stand. They found visibility could be dealt with in a number of ways including: using the harvester head to clear regeneration near the base of trees, respacing ahead of the harvest, placing the harvester head higher on a stem and then running down to the felling cut level and use of some motor manual harvesting. Ireland (2009) followed up with another study at Clocaenog, final over
story removal in a stand being transformed to CCF. Mean DBH and mean volume per stem were as in the earlier study, though in this final felling, some trees exceeded the capacity of the harvester owing to DBH, buttressing and coarse branching. Motor manual harvesting was necessary above 55 cm DBH. All of these UK studies provided useful insights on the conduct of time studies and as well some useful points to consider in planning the Stourhead (Western Estate) research. However, none represent, nor were represented as being reflective of harvesting in a well-developed irregular forest environment.

Similarly to the UK, Sweden has recognised there may be merit in having some element of uneven-aged forests in pursuit of better biodiversity and environmental sustainability. Skogforsk’s Rikard Jonsson (2015) conducted a harvesting study with the objective of starting to evaluate the comparative costs of harvesting between even-aged and uneven-aged stands given a public policy move toward having 5-10% of forest area dedicated to uneven-aged stands in the future. Jonsson had limited choices of forests in which to conduct his work. Jonsson acknowledged the early stage of his work and suggested more research would be needed. He noted a direct relationship between stem size and harvester productivity and theorised that the lower density of trees (less stems/hectare) and need for operator-select during harvesting would contribute to greater time elements associated with manipulating the harvester crane during harvesting. Jonsson’s recent work contributed to planning for the Stourhead study, and provided one somewhat comparative set of results for comparison with Stourhead.

2.4 Objectives and scope of the present research

The literature review confirmed the views of Knoke (2012) and Puettmann et al (2015), ultimately harvesting cost implications for irregular forests were not yet sufficiently researched. Further, it would seem the need for such data is undeniable. Over time, authors have sought to run comparative economics for uneven-aged versus even-aged silviculture without the benefit of empirical data on a number of fronts, including harvesting costs. Price, C. (2007) was better positioned than most in that he had recent harvesting data, albeit from a forest in transformation to
uneven-aged, from the work of Price, M. (2007). Tahvonen et al (2010) constructed a model to determine the optimum management of uneven-aged Norway spruce (*Picea abies*) stands compared to even-aged in Finland and Sweden. While focus appears to have been on the growth model, it is acknowledged the harvesting cost input came from the 1994 work of Kuitto in even-aged forests. Tahvonen (2011) went on to assess the economics of uneven-aged Norway spruce (*Picea abies* (L.) Karst.) in the Nordic countries to challenge the view of economic superiority of even-aged management. Harvesting costs were again from Kuitto but factored by 1.15 for uneven-aged. It is unclear whether that factor had been applied in the previous study. Owing some growth in support to change Finland’s forest law to allow uneven-aged stands, Pukkala et al (2010) constructed an economic model for uneven-aged Norway spruce and Scots pine (*Pinus sylvestris*) stands. The model used a harvesting cost model of 1992 vintage for a thinning treatment. Finally Hanewinkel et al (2013) in Switzerland and Davies & Kerr (2015) did economic analyses of uneven-aged forests and forests in transformation to continuous cover respectively. Both used relatively recent harvesting cost data but had to make theoretical adjustments to empirical data for use in their evaluations.

The primary objective of the research was to quantify harvesting productivity in areas which represented the range of stand structures, harvesting techniques and terrain conditions experienced at Stourhead. Further objectives were:

1) establish harvesting costs per cubic metre for the study areas based on the type of equipment used and a transparent method of costing for that equipment,

2) develop harvesting productivity regression equations, particularly for the irregular stand, which might be employed to predict harvesting costs for future interventions.

Insight and data gained in the harvesting study potentially could be used for future economic modelling and decision-making. In particular, the regression equations could facilitate a more empirical assessment of the full cycle costs of irregular silviculture at Stourhead (full regular cycle versus similar irregular time period) and ultimately perhaps other areas of lowland conifer forests in the UK.
3 Methods

3.0 Overall site description

Stourhead (Western) Estate is located in southwest Wiltshire in the South West region of England at an elevation up to 210 metres AMSL. Local yearly average rainfall and temperature are about 860 mm and 10°C respectively (Met Office, 2018) based on the nearest weather station. It is believed precipitation is higher locally with a range of 950 - 1050 mm given by the forest managers. The forested area covers 652 hectares of which about 75% is coniferous. Poore (2007) provided an excellent account of the local geology, which can be summarised as Cretaceous Upper Greensand and underlying Gault clay with parts of the forest lying on the north western slope of a large escarpment and the remainder lying behind the escarpment in an area of post-glacial land slips. That created a varied topography, dry slopes punctuated by springs and wet ground at exposures of the Greensand/Gault boundary and generally acidic soils.

As described in Poore (2007), there is a rich history of forest management at Stourhead beginning in the 18\textsuperscript{th} Century, with systematic management evident from the beginning of the 20\textsuperscript{th} Century. A desire to avoid large-scale disturbance to protect views on the estate led to a silvicultural practice of small-scale group felling. By late in the 20\textsuperscript{th} Century, that had created a mosaic of over 1200 small even-aged units and set the stage for future management toward an irregular structure by single tree selection harvesting. The result has been that in places Stourhead now has compartments with well-developed irregular structures.

3.1 Study plot characterisation

Selection of study areas was done in consultation with the forest managers. Criteria for inclusion were: planned harvest in spring/summer of 2016, distinctive and differentiated harvesting methodology and, at minimum, underlying regular and irregular silvicultural treatments. Ultimately four study areas were chosen:

- Hand fell down a steep slope to the harvester stationed on a forest road; compartment in transformation to an irregular structure – the ‘Slope Tract’,
• Primary harvest by harvester, also motor manual butt preparation, motor manual felling of stems greater than 60 cm and winching or skidding as required for timber too large or out of reach of the harvester; compartment well developed toward irregular – the ‘Irregular Tract’,
• Hand fell on a steep slope, winch recovery to top of slope for harvester processing; compartment in early transformation – the ‘Winch Tract’,
• Full harvest by harvester; regular tract 3rd thinning - the ‘Regular Tract’.

Those represented the range of harvesting conditions currently experienced at Stourhead and would provide insight to harvesting productivity and costs. Table 3.1 provides an overview of the chosen areas.

**Table 3.1** Harvesting study areas

<table>
<thead>
<tr>
<th>Woodland Name</th>
<th>Sub-cpt.</th>
<th>Area (ac)</th>
<th>Planting Dates/Species¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Great Combe (Slope Tract)</td>
<td>102b</td>
<td>1.53</td>
<td>1950/DF</td>
</tr>
<tr>
<td>Great Combe (Irregular Tract)</td>
<td>103a</td>
<td>4.89</td>
<td>1903/1923/1963/DF</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1963/RC/WH</td>
</tr>
<tr>
<td>Little Combe (Winch Tract)</td>
<td>104a</td>
<td>0.86</td>
<td>1996/WH</td>
</tr>
<tr>
<td>Kingswood Warren (Regular Tract)</td>
<td>807c</td>
<td>2.67</td>
<td>1991/DF/SS</td>
</tr>
</tbody>
</table>

¹ Pengelly (2015a, b, c)

Consideration was initially given to replicating each of the study areas. However, owing to the highly variable, mosaic character of the forest, it was apparent on inspection that only in the Kingswood Warren woodland would such a replicate be possible. It was deemed more appropriate to have larger single study areas than attempt to create replication where that was not practical.

**3.1.1 Study plot and rack layout**

Once study areas were generally agreed, the plots were set out by stakes with white top marks, and where necessary, enough brush cut to achieve line of site. A Garmin GPSMAP® 60CSx was used to mark station points and determine areas of the study
plots (Table 3.1). Data was also collected for leg distances, bearings and slopes between recorded stations with a Walktax\textsuperscript{®} string measuring box, Suunto KB-14/360R G compass and Suunto PM-5/1520 height meter to aid in re-establishment of plots in future should that prove desirable.

The author did not find it common that published harvesting study papers identified the means by which areas were established. However, in Price, M. (2007) it was apparent study plots were set out much as stated above, only to be followed by a professional survey. The reason given for that, learned in email correspondence (Price, 2016), was that at the time it was thought the study areas might be re-evaluated in the future and the Forestry Commission wished to be able to accurately re-establish the plots.

Areas were not immediately critical to the objectives of this harvesting study; however, those did allow a more thorough description of the site, e.g. basal area per hectare removed could be calculated from the sum total of measured basal areas of harvested stems. It should be noted that the Irregular Tract was largely coincident with sub-compartment boundaries so an accurate mapped area was available for that plot – though little different from the GPS area.

Rack layout was only relevant to the Irregular and Regular Tracts. The other two harvesting areas did not require racks as such, but used established forest roads for access down-slope or up-slope. Racks had not been established in the Irregular Tract since previous harvesting had been done by motor manual with winch extraction. After consideration of site-specific conditions and with reference to published work of Bacher (2003), Bacher-Winterhalter (2003) and Mederski (2006), it was decided to roughly double the common rack spacing found in regular forests to 37-40 metres for the Irregular Tract.

Bacher/Bacher-Winterhalter was early in the study of mechanised harvesting in permanently irregular stands. She determined that smaller rack spacing would be too intrusive to the desired structure (and take up growing space) and therefore adopted 40 metre racks. Trees out of reach of the harvester in the middle zone (circa 20 metres) would be hand-felled toward the harvester, as would trees greater
than 55 cm DBH which approached the working limits of the boom. Mederski, a few years later, and with the same logic as Bacher, did a comparative study of harvesting productivity and costs with the normal rack spacing of 18-20 metres versus a so-called midfield strategy very similar to Bacher’s of 35-38 metres. Both authors reported very positive results with the comparative study of Mederski showing a harvester productivity improvement ranging from 30-32% and forwarder productivity improvement ranging from 11-27%, while cost improvement ranged from 14-18% for harvesting and 11-18% for forwarding. These results gave confidence to the spacing of permanent extraction racks for the Irregular Tract.

The Regular Tract at Kingswood Warren already had an established rack layout on 20 metre spacing and there was no need to change that.

### 3.1.2 Pre-harvest mensuration

While laying out the study plots and racks, the opportunity was taken to further characterise the study areas. With the exception of the Irregular Tract, pre-harvest basal area was determined by the relascope principle as defined in Philip (1994) using a prism of BAF 2 (basal area factor). A Haglöf IV® hypsometer was used to measure top heights, again excepting the Irregular Tract. The Irregular Tract was part of a complete enumeration in early 2016 which provided deterministic data for the wider sub-compartment and, separately, the study area (Poore, 2016).

Terrain was classified by the method adopted in 1974 by the Forestry Commission adapted from the Scandinavian system (Rowan, 1977; Forest Research, 1996). That system classifies terrain according to ground conditions (bearing capacity of the soil), ground roughness (obstacles impeding movement) and slope. The study areas generally had good to average ground conditions (rating of 2-3), very good to good roughness (rating of 1-2) and slope ranging from gentle to steep (rating of 2-4). The Suunto PM-5 optical height meter was used to more precisely characterise slope by measuring that along strike of the study plots.

Table 3.2 contains a further summary of the descriptive statistics for the study plots and Figure 3.1 shows the diameter frequency distribution in the Irregular Tract,
adapted from Poore (2016). That distribution demonstrates substantial
development toward an irregular structure. The 2016 intervention in the Irregular
Tract, which was later than planned by circa two years, was intended to redress the
modest frequency of the smaller diameter classes through encouraging more
natural regeneration.

Table 3.2 Study area descriptions

<table>
<thead>
<tr>
<th>Study Area</th>
<th>BA¹ (m²/ha)</th>
<th>Top Height¹ (m)</th>
<th>Terrain Class.²</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope Tract</td>
<td>36.5</td>
<td>37.4</td>
<td>2.2.4</td>
<td>18.9-25.0°</td>
</tr>
<tr>
<td>Irregular Tract</td>
<td>40.4³</td>
<td>Full enumeration</td>
<td>2.1.2</td>
<td>8.7-9.5°</td>
</tr>
<tr>
<td>Winch Tract</td>
<td>39.3</td>
<td>26.9</td>
<td>2.2.4</td>
<td>22.8-24.6°</td>
</tr>
<tr>
<td>Regular Tract</td>
<td>36.0</td>
<td>20.2</td>
<td>3.2.2</td>
<td>5.5-7.0°</td>
</tr>
</tbody>
</table>

1 Pre-harvest  2 Forest Research (1996)  3 Poore (2016)
Figure 3.1 Irregular Tract diameter frequency distribution (Poore, 2016)

3.1.3 Stem removals marking and measurement

Subsequent to lay out of the study areas, the author worked with the forest manager to mark removals in all except the Irregular Tract. All of the areas are or will be managed on a selection basis, so focus was on removal of poor form or weak growth stems along with an eye to regeneration where appropriate. Target basal area removal was about 20%.

Trees to be felled were numbered with forestry marking paint in at least three quadrants at about 1.8 metres above ground level. That assured that during harvesting the harvester operator and the work study person, the author, could readily identify trees to be felled regardless the direction of approach. DBH at 1.3 metres, tree number and species were recorded for each marked tree. Diameters for the Slope Tract and Irregular Tract, which contained sizeable timber, were obtained with Haglöf 50 cm or 80 cm calipers with two readings taken at 90° and averaged. For those stems greater than the range of the 80 cm calipers, a Lufkin® W606PD diameter tape was used. For the smaller trees of the Winch and Regular Tracts, it was found that the diameter tape was quicker. In theory the diameter tape is more accurate, particularly where stems are not round. However, a random
sampling of tape versus calipers showed little difference for the growing stock on the Winch and Regular Tracts. Mensuration practices as established by experts in the field were applied throughout (Matthews & Mackie, 2006; Philip, 1994).

At the outset, data was recorded on 4” x 8” tally cards made by Forestry Suppliers, Inc. (Stock No. 53690), though direct recording into Excel on a Samsung Galaxy Tab4 (7”) handheld computer was also tried and then exclusively used for the Winch and Regular Tracts. While the tally cards and pencil cannot be exceeded for dependability, the tablet computer, with extreme care in data entry, yielded large time savings in subsequent data processing with no risk of data transposition errors. Recording calipers would have been even better for efficiency of data collection. Table 3.3 shows mean diameter statistics and mean volumes for stems marked for removal. The volumes are as derived from harvester on board computer (TM300) data captured during the harvest except for the extra-large Douglas fir which were manually measured.

Table 3.3 Study area stem removals statistics

<table>
<thead>
<tr>
<th>Study Area</th>
<th>Mean DBH (cm)</th>
<th>QMD¹ (cm)</th>
<th>Std.² Dev.</th>
<th>Range</th>
<th>Mean Vol.³ (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope Tract</td>
<td>47.0</td>
<td>48.0</td>
<td>10.0</td>
<td>27.0 - 74.0</td>
<td>1.8</td>
</tr>
<tr>
<td>Irregular Tract</td>
<td>42.0</td>
<td>45.0</td>
<td>15.5</td>
<td>21.0 - 75</td>
<td>1.0</td>
</tr>
<tr>
<td>Extra Large DF</td>
<td>110.2</td>
<td>110.3</td>
<td>4.5</td>
<td>105.0 - 118.0</td>
<td>13.4</td>
</tr>
<tr>
<td>Winch Tract</td>
<td>30.3</td>
<td>31.6</td>
<td>8.8</td>
<td>17.0 - 52.4</td>
<td>0.7</td>
</tr>
<tr>
<td>Regular Tract</td>
<td>16.6</td>
<td>17.4</td>
<td>5.9</td>
<td>7.0 - 36.0</td>
<td>0.2</td>
</tr>
</tbody>
</table>

1 Quadratic mean 2 SD of mean 3 TM300
3.1.4 Felled timber measurement

At an early stage it was hoped to use the facility of the harvester’s on-board computer to capture log data for the harvester aspect of the time study. However, it became apparent that the unit in the planned harvester, a Timbermatic™300, was only used to set cutting lengths and not regularly calibrated. So alternative manual plans were made, while still hoping to have the TM 300 as a cross-check on single tree and overall harvested volumes. In any event, the forwarding time studies required measurement details to be identifiable to logs on the ground, so physical measurement had to be done.

Application of technology to forwarders, the simplest being mass measurement, has lagged well behind the technology applied to harvesters. Jaeger et al (2010) recognised this gap in harvesting information technology. They researched enhanced calibration of harvester measurement devices such that log volume information could be combined with photo-optical log count methods to fill the information gap. Results were promising. However, within the period of this time study of forwarding productivity, and that of e.g. Nurminen et al (2006), Price, M. (2007), Ireland (2008) or even Jonsson (2015), detailed analysis of forwarding productivity has required manual marking and measurement of logs, and for tree level analyses, placement of products in tree-wise bundles. The latter, based on this author’s observations, would impose an unnatural sequence on the forwarder operator owing to the large selection of stem sizes processed. Therefore, for this time study, from the outset it was determined that it was impractical to measure forwarder productivity at tree level. Productivity was measured at an aggregated level, e.g. by rack, to achieve some measure of analytic ability for the forwarder.

The first area to be harvested, the Slope Tract, required motor manual felling toward a track where the harvester was to pull in the stems for processing. The sequence of activities was such that it was possible to measure the timber length and mid-diameters of the felled trees, followed by numbering and measuring of all logs of each individual tree. Length measurements were taken with a U.S. Tape Company, Inc. Spencer Original LoggersTape™ 900MED while mid-length diameters
were done with calipers, two readings at 90°. The data collection allowed a three way comparison of volumes, which will be discussed in the results section. All subsequent volume calculations were done by the mid-diameter equation, *Huber’s formula* as found in e.g. Matthews & Mackie (2006).

With regard to the Regular Tract, the speed of harvesting and processing combined with the large number of small products made individual tree tracking impossible, or that would only have been possible with substantial interference in the normal harvesting activity. Since there was no intent to do in-depth analysis of the elemental work break downs for the Regular Tract, aggregate volumes were established for each rack post-harvest. Each log was numbered and lengths and diameters measured as above. All data was recorded directly into Excel on the Samsung handheld computer owing to the larger number of logs, nearly 1500.

In summary, log measurement was fundamentally a manual process using tape and calipers with the majority of data directly entered into Excel on the Samsung tablet. Substantial care was taken with these measurements. The work of Strandgard (2009) demonstrated the impact that the manual measurements which are used in harvester calibration procedures can have on resultant on board computer data. That data can be no better in quality than the quality of the manual measurements used to set up the machine. His research took issue with previous work by e.g. Nieuwenhuis & Dooley (2006) that tacitly assumed the accuracy of manual measurements. Owing to generally very good stem form, little branchiness and square end cuts, manual measurement is believed to have been suitably accurate during the study.

### 3.1.5 Study areas pre-harvest photographs

Figures 3.2 – 3.5 show the study areas pre-harvest. The differences between the study areas are clear to see. The Slope Tract was a 1950 planting of Douglas fir, with the last intervention in 2008. The Irregular Tract, as described in Table 3.1 had a number of species planted at various times from 1903. The white slashes mark a planned extraction rack. Some young regeneration can be seen in the photo. The
last harvest was in 2009. The Winch Tract, planted in 1996, was at a much earlier stage of selection harvesting as can be inferred from the photo. It was last worked in 2008. Finally, the Regular Tract appears as one would expect to see in an even-
aged stand which was last thinned in 2011 – small trees, evenly spaced and no undergrowth.

3.2 Work study methodology

The various approaches to work study, including direct observation, video and analysis of harvester-captured data were discussed in the literature review. With respect to direct observation and video, while authors stated the method used, none stated why a particular approach was adopted. Use of harvester-captured data was a developing technology, so literature was available which compared the pros and cons of machine-captured data versus physical observation, e.g. Strandgard (2013). The main disadvantage of machine-captured data was the lack of insight into the physical conditions during harvesting and unexpected work during a cycle, e.g. dropping a stem during processing. This lack of direct observation ruled out a machine-data approach to this research, notwithstanding it was later apparent the relevant harvester lacked the facilities to capture, or reliably capture, data.

In the absence of discussion by authors on why they chose direct observation or video technology and the associated software and hardware, this author contacted a number of time study researchers who were well-published in the field. The literature review had led to an initial view that video would be the preferred method owing to immediate access to a video camera and the theory that ability to replay events would be helpful during analysis. Choice of work study software was not assisted by the literature review.

In email correspondence with Strandgard (2016), Eliasson (2016), Klepac (2016) and Ovaskainen (2016) several themes emerged:

1. Video can suffer from lack of light, undergrowth interference and limited field of vision.

2. Video, if used alongside direct observation, can at times fill data gaps or resolve data entry errors.

3. Subsequent analysis of video data is extremely time-consuming.
4. Use of harvester-captured data has much application, e.g. mill planning, comparative performance of operators, large scale backward looking studies; however, traditional time study methods are still required to address many specific research questions.

5. Limit the number of elements of work in a particular study to those required to answer the research question.

Researchers typically used handheld ruggedised computers for data capture, with the products of Juniper® Systems, Inc. (Archer or Allegro models) being common. Timer Pro™ work study software was used by three researchers, with mixed reviews, whilst one, Eliasson (2016) of Skogforsk used the Haglöf product SDI (Skogforsk Data Information) developed in conjunction with Skogforsk. Ultimately, on cost and practicality grounds, a solution of Timer Pro™ Professional software running on a Samsung Galaxy Tab4 (7.0”) was chosen. That software could easily be customised by the author, whereas the SDI solution would have required Haglöf support (Gustafsson, 2016). While one cannot compare the Samsung to the Juniper™ Systems products, the combined cost of a working system was at £750 (Aird, 2016), one-third that of the alternative (Wikner, 2016). In practice the Samsung supported by a power bank for long days was adequate for the work and the software, after initial teething issues, performed well.

3.2.1 Research comparability

Björheden et al (1995) proposed standards be set for forestry work studies to enhance comparability of studies being done across the industry. Years later, Magagnotti & Spinelli (2012) believed the once reasonably common study methods had been lost. They edited a European COST Action report which, while under the context of biomass production studies, set out to re-establish, or at least establish for biomass production studies, a commonality of approach, including terminology, units of measure and reporting guidelines. This author attempted to take due note of that work, and in particular recommendations on reporting. Of particular note were recommendations on the definition of delays.
Spinelli & Visser (2008) recognised that delays can be a major factor in harvesting studies, yet can be erratic and difficult to assess. They evaluated delays across 34 time studies of which they had direct knowledge to better understand what norms might look like. One finding was that 94% of delay events were less than 15 minutes, and many European countries had not counted delays less than 15 minutes in their assessments of productivity. The work of Spinelli & Visser led to calculation of delays based on their recommendations – all delays count and delay time was assessed in relation to productive work time, not total time.

3.2.2 Work study elemental structure design

Programming of the work study software required design of work cycle and data entry templates for each of five methods used across the study areas: chainsaw, harvester, forwarder, winch tractor and skidder. While elemental recording was most important for the Irregular Tract (owing to the objective of development of predictive equations for harvesting productivity), it was decided to capture data at the same elemental level for all study areas. Elemental work breakdown structures generally followed those of e.g. Jonsson (2015), Ireland (2009), Price, M. (2007), and Nurminen (2006), particularly for the main work elements. The advice of especially Eliasson (2016) and Ovaskainen (2016) was taken to limit the number of work elements both to make data entry manageable and in respect of the objectives of the study.

Appendices I – V contain screenshots of the work cycle programming for each of the five harvesting methods. The entries in the column labelled ‘1st Level’ represent the main elements of work and displayed as colour-coded, labelled touch-sensitive boxes on the Samsung screen. The further levels, which carried additional information, e.g. number of logs, were directly accessible from the 1st Level screen. Each harvesting method programme also contained descriptive data for the particular study: location, equipment in use, operator name, terrain and weather. Preprogrammed standard notes were also available for ease of quick entry. The note function, importantly, provided the means to identify specific numbered trees to e.g. a work cycle of the harvester.
Delay time was programmed in the basic categories identified by Spinelli & Visser (2008) – mechanical, operator and operational - with some common operational delays, e.g. refuelling, preprogrammed for ease of data entry.

3.2.3 Selection of products cut

Owing to the nature of the study areas and previous silvicultural history, there was a variety and species and sizes which combined to make the selection of products cut much greater than experienced in any of the studies in the literature. The timber specification for the relevant stand was embedded in the work study programme. See Appendix VI for the timber specification for the Great Combe study areas (Guest, 2016).

3.3 Costs of harvesting

Machinery used for this study was as follows:

1. Harvester – John Deere 1470D with H480 head, maximum cut 72 cm
2. Forwarder - Rottne Solid F12 with RK 80 crane
3. Winch tractor – Valmet 8150 with BGU FSW9.5te HV winch
4. Skidder – Timberjack 380C with winch and grapple
5. Chainsaws – a range including Sithl MS391, 441 and 660

With the exception of the winch tractor and chainsaws, the remaining equipment was ten or more years old. As found in the literature review, access to actual cost data for harvesting equipment is difficult. That is not wholly surprising owing to an understandable view that such information is commercially sensitive. The author believed the work of KWF in developing and publishing operating cost calculation spreadsheets (KWF, 2016a) was the best available approach to costing short of a separate comprehensive study. An advantage of the KWF spreadsheets is the comprehensive nature of the included items such that if one decides to reset variables such as useful life or yearly operating hours, assume used machinery, or indeed ignore certain areas such as overheads, then at least the impact on resulting
hourly operating costs would be apparent. As a final sense check on the output figures (converted to GBP at the 2016 average exchange rate), those for the major machinery were reviewed with John Deere UK (McKie, 2016) and found to be in an expected range. Table 3.4 shows the hourly operating rates used for machinery during the study. Those rates are fully inclusive of overheads and operator.

Table 3.4 Harvesting machinery operating costs

<table>
<thead>
<tr>
<th>Machine</th>
<th>Rate (£/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvester</td>
<td>150</td>
</tr>
<tr>
<td>Forwarder</td>
<td>95</td>
</tr>
<tr>
<td>Skidder</td>
<td>75</td>
</tr>
<tr>
<td>Winch tractor</td>
<td>50</td>
</tr>
<tr>
<td>Chainsaw</td>
<td>35</td>
</tr>
</tbody>
</table>

4 Results

4.0 Overview of harvesting operations

Subsequent to study plot marking and mensuration, harvesting operations were conducted over an elapsed time period of 41 days from early April through late May of 2016. Weather conditions were dry most of that time with only scattered days of light rain. The equipment as identified in section 3.3 and the same operators were used throughout the period. The harvester had a significant mechanical failure and the forwarder experienced recurrent minor repair issues which extended the time on site. Other equipment performed with no mechanical faults.

All sites except the Regular Tract required harvesting measures in addition to the harvester and forwarder. Therefore productivity (m³/h) was calculated for each machine for the volume that machine processed. Similarly, harvesting cost per unit volume (£/m³) for each machine was calculated and the resultant elements
summed in proportion to volume processed to yield an aggregated harvesting cost. That required careful accounting of volumes harvested by each method and acknowledgement that different means of volume measurement were being employed. It was found in practice that the Stourhead (Western) Estate (SWE) single entry tariff tables, developed over many years, yielded a good comparison to the harvester’s volume measurement, and that tape and calipers of products were consistently high. Therefore all non-harvester volumes were adjusted based on the calculated ratio between harvester volumes and hand-measured volumes. That was believed preferrable over failing to acknowledge the differing measurements. Table 4.1 shows the volume relationships found for the Slope Tract as an example. Subsequent caliper and tape measurements were within 5% of harvester volumes.

Table 4.1 Slope Tract timber volume measurement

<table>
<thead>
<tr>
<th>Method</th>
<th>Volume (m³)</th>
<th>Percentage Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWE Single Entry Tariff</td>
<td>29.8</td>
<td></td>
</tr>
<tr>
<td>Harvester Timbermatic 300</td>
<td>30.2 (+1.3%)</td>
<td></td>
</tr>
<tr>
<td>Whole Tree Calipers &amp; Tape</td>
<td>33.0 (+10.7%)</td>
<td></td>
</tr>
<tr>
<td>Products Calipers &amp; Tape</td>
<td>34.6 (+16.1%)</td>
<td></td>
</tr>
</tbody>
</table>

This results section covers each study area in succession and includes a selection of the results deemed most important to the objectives of the study. Productivity performance of each component part of the harvesting is presented before concluding each study area section with overall productivity and cost results. When shown, productivity graphs often give regression analyses for both quadratic and power functions with observations as relevant. The order of presentation follows the order of the work, which was purposefully programmed to allow a lead-in to the Irregular Tract and lowest priority to the Regular Tract. The full results extend to over ninety pages of data and calculation spreadsheets not including the raw data and are electronically accessible for further research. Printed booklets of calculations and graphs (Figure 4.1) were invaluable to quickly cross-refer between processed data and calculation worksheets during analyses.
4.1 Slope Tract results

The Slope Tract was representative of wooded slopes rising toward the high plateau at Stourhead. A road network had been established along strike to accommodate previous motor manual and winch extraction harvesting practices. That left relatively narrow woodlands on steep ground inaccessible to harvesters. The Slope Tract, along with many others at Stourhead, is managed under a selection system, with encouragement of natural regeneration and movement toward an irregular structure.

Sixteen trees of average diameter 47.0 cm were felled by chainsaw downslope toward the logging road where the harvester could then process them. Subsequently the forwarder was able to recover all except three logs, which required winch extraction. So this operation required use of all harvesting methods bar the heavy skidder.
4.1.1 Chainsaw felling Slope Tract

This activity was unremarkable and accurately accomplished by the feller at a purposeful pace. Time study was done, notwithstanding the small sample volume. Figure 4.2 presents a regression chart with independent variable diameter and dependent variable felling time. (Arithmetic means for diameter have been used throughout to conform with the apparent practice in other studies. Quadratic mean is more correct (Curtis & Marshall, 2000) though as shown in Table 3.3 the differences are not great.) Owing to the nature of the work, both quadratic and power functions were tested. $R^2$ shows a reasonable goodness of fit for either; however, no definitive conclusions should be drawn. The performance was captured for potential use in future predictive analyses at Stourhead.

Figure 4.2 Chainsaw felling Slope Tract

4.1.2 Harvester processing Slope Tract

The harvester performed well operating from the forest road, dragging in the felled trees by their tops for processing. With the exception of one 72” diameter log, 5 metres long, all timber was processed. Chain sharpening and then replacement caused some delay. The views of Björheden et al (1995) and Magagnotti & Spinelli (2012) come to the forefront when processing and analysing productivity data for a harvester. It is necessary to test relationships to independent variables (and
variations of those), adapt analyses to the goals of the study and arrange results for some level of comparability with other work. Figures 4.3 – 4.6 demonstrate those aspects.

Figure 4.3 demonstrates the type of analysis that could be readily captured in the field to extend the results of this study. Both time consumption and DBH are reasonably obtainable for any confirmation studies. The coefficient of determination shows that DBH is a reasonably good sole value predictor. Figure 4.4 tests work rate versus DBH, which is less intuitive, but does appear in the literature, e.g. (Price, M., 2007). Figure 4.5, time consumption versus volume, is effectively a check on the degree to which DBH alone describes a stand, and a form of such was commonly seen in harvesting studies. Figure 4.6, work rate versus stem volume is also commonly seen in the literature.

These results are of course lacking the work element of felling, and are specific to a particular harvesting scenario at Stourhead, but one which will continue for the foreseeable future. Figures 4.3 and 4.5 suggest that DBH and stem size are good predictors for harvesting time and productivity respectively. The power function might have been expected to yield a better fit if the harvester was approaching its operating capacity; however, that was not apparent in this harvesting operation.

Figure 4.3 Harvester processing Slope Tract – time versus DBH
Figure 4.4 Harvester processing Slope Tract - time/volume versus DBH

![Graph showing time/volume versus DBH](image)

- Equation: $y = 0.1302x^2 - 13.617x + 557.63$
- $R^2 = 0.2165$

- Equation: $y = 400.7x^{0.164}$
- $R^2 = 0.0223$

Figure 4.5 Harvester processing Slope Tract – time versus size

![Graph showing time versus size](image)

- Equation: $y = 56.325x^2 + 6.0838x + 167.79$
- $R^2 = 0.7313$

- Equation: $y = 237.38x^{0.8128}$
- $R^2 = 0.7081$
4.1.3 Forwarding Slope Tract

Only two trips of the forwarder were required to recover all but three logs. In each case, distance from the log landing to the harvesting site was 417 metres, an attribute of the well-developed forest road system at Stourhead. Loading distance along the recovery track was 132 metres, so overall distances were low. As shown in Table 4.2, the saw logs were recovered in Load 1 while the small wood was recovered in Load 2, with both loads being near capacity of the forwarder.

Table 4.2 Forwarder productivity Slope Tract

<table>
<thead>
<tr>
<th>Load</th>
<th># Pieces</th>
<th>Mean Volume m³</th>
<th># Load Cycles</th>
<th>Load Volume m³</th>
<th>Time (minutes)</th>
<th>Productivity m³/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35</td>
<td>0.419</td>
<td>8</td>
<td>14.679</td>
<td>29.158</td>
<td>30.2</td>
</tr>
<tr>
<td>2</td>
<td>70</td>
<td>0.211</td>
<td>18</td>
<td>14.734</td>
<td>42.135</td>
<td>21.0</td>
</tr>
<tr>
<td>Total</td>
<td>105</td>
<td>0.280</td>
<td>26</td>
<td>29.413</td>
<td>71.293</td>
<td>24.8</td>
</tr>
</tbody>
</table>

Unsurprisingly, productivity was higher with the lesser number of larger volume saw logs. That is further borne out by the elemental work breakdown structure results as shown in Table 4.3 where loading and travel loading times are greater for
the small wood. Overall the forwarding data provides some data for comparison especially with harvesting the larger timber in the Irregular Tract, but insufficient data for any in-depth statistical analyses.

Table 4.3 Forwarder work breakdown structure results Slope Tract

<table>
<thead>
<tr>
<th>Load</th>
<th>Travel Empty (%)</th>
<th>Load (%)</th>
<th>Travel Loading (%)</th>
<th>Travel Loaded (%)</th>
<th>Unload (%)</th>
<th>Travel Unloading (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.1</td>
<td>31.2</td>
<td>6.0</td>
<td>19.6</td>
<td>28.1</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>10.5</td>
<td>36.8</td>
<td>13.9</td>
<td>11.9</td>
<td>24.6</td>
<td>2.3</td>
</tr>
<tr>
<td>Average</td>
<td>12.4</td>
<td>34.5</td>
<td>10.6</td>
<td>15.0</td>
<td>26.1</td>
<td>1.4</td>
</tr>
</tbody>
</table>

4.1.4 Winching Slope Tract

Only three logs required recovery by winch, though those totaled nearly 5 m³ in volume. While time study data was captured, that was more in the context of testing the work study process which had been programmed in the Samsung than doing a concerted time study on such a small sample.

4.1.5 Slope Tract overall productivity and cost results

Table 4.4 shows the overall results for the Slope Tract, which had trees of average DBH 47 cm and average volume of 1.8 m³ as shown in Table 3.3. Volumes processed by each method are shown as well as delay free and total (with delay) values for productivity and cost. Delay factors were in the same range as seen in other studies, e.g. Ireland (2008). The total harvesting costs were calculated in respect to the fraction of the total volume which that method used, e.g. the harvester processed 28.2/30.0 of the total volume so contributed to cost at that ratio.
Table 4.4 Slope Tract overall results

The Irregular Tract represented a well-developed irregular structure within the Stourhead (Western) Estate. A diversity of species, sizes and ages of trees was apparent, as well as a notable amount of natural regeneration of especially Western red cedar (*Thuja plicata*) and Douglas fir (*Pseudotsuga menziessi*). This tract required employment of all harvesting techniques.

There were also a number of extra-large Douglas fir to harvest. Those were felled after the main harvest and that activity was analysed as a separate activity, covered as the last topic in this section. As with the previous section, only a selection of the most relevant results are presented.

### 4.2 Irregular Tract results

<table>
<thead>
<tr>
<th></th>
<th>Volume</th>
<th>Delay Free Prod.</th>
<th>Total Prod.</th>
<th>Delay Factor</th>
<th>Rate per hour</th>
<th>Delay Free Cost</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvester</td>
<td>28.2</td>
<td>20.4</td>
<td>16.0</td>
<td>27.6</td>
<td>150</td>
<td>7.35</td>
<td>9.38</td>
</tr>
<tr>
<td>Forwarder</td>
<td>25.7</td>
<td>21.6</td>
<td>16.7</td>
<td>29.6</td>
<td>95</td>
<td>4.40</td>
<td>5.69</td>
</tr>
<tr>
<td>Winch</td>
<td>4.5</td>
<td>11.9</td>
<td>11.9</td>
<td>0.0</td>
<td>50</td>
<td>4.20</td>
<td>4.20</td>
</tr>
<tr>
<td>Chainsaw</td>
<td>30.0</td>
<td>15.7</td>
<td>12.2</td>
<td>29.1</td>
<td>35</td>
<td>2.23</td>
<td>2.87</td>
</tr>
</tbody>
</table>

**TOTAL HARVESTING COSTS**

|                  | 13.54  | 17.18

### 4.2.1 Chainsaw felling Irregular Tract

As discussed in the Methods section, extraction racks were set at circa 40 metres, which required directional felling of timber in the mid-field toward the reach of the harvester. That felling along with debutting Western red cedar as necessary and felling any trees in excess of 60 cm DBH was done prior to arrival of the harvester. A total of 30 trees were felled by chainsaw, while 5 required buttress removal to
allow the harvester head access for felling. Twelve butt logs were also crosscut owing to size (diameter or weight) beyond the harvester’s expected limits. The felling was mostly straightforward with little damage being done to regeneration and only one tree hung up in a well-stocked stand. Average DBH was 51.3 cm with a maximum of 75.0. The work study showed debuttressing as the most time consumptive element (32.4%) while walking between trees (19.1%) and felling (14.3%) were the next two in order. The varied use of the chainsaw meant regression analysis held little promise; however, analyses were run for felling/debuttressing as shown in Figure 4.7. That does not provide as high a coefficient of determination, as for the Slope Tract. However, separate analyses by species showed the Douglas fir alone showed a coefficient of determination of 0.71. The highly variable impact of buttresses on the Western red cedar accounted for the deterioration of the relationship between DBH and felling productivity.

Figure 4.7 Chainsaw felling/debuttressing Irregular Tract

<table>
<thead>
<tr>
<th>Chainsaw (Fell/Debutt) Irregular Tract</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Graph" /></td>
</tr>
<tr>
<td>y = 0.2327x² - 7.3375x + 467.02</td>
</tr>
<tr>
<td>R² = 0.471</td>
</tr>
<tr>
<td>y = 13.731x^{1.005}</td>
</tr>
<tr>
<td>R² = 0.5469</td>
</tr>
</tbody>
</table>

4.2.2 Harvester Irregular Tract

The harvester handled 68 trees of mean DBH 42.0 cm and mean volume 1.0 m³ during harvesting the Irregular Tract. Thirty of those had been chainsaw felled, so the ‘felling’ work element was missing in the cycle times for those trees. Based on the operator’s experience, all trees exceeding 60 cm near the cutting zone were
felled by chainsaw before harvester arrival. In practice, notwithstanding the 72” maximum capacity of the harvester head, trees in excess of 55 cm at times required more than one felling cut. The 60 cm criteria was clearly at the limit of the harvester.

Analysis of the data took cognisance of the different species and also the fact that the harvester fully processed 56% or the trees, while the remainder had already been felled. However, average cycle time for felling only comprised on average 7.2% of the elapsed time to fully harvest a tree. The largest work element at 42.4% of elapsed time was machine movement along the rack, followed by processing at 37.5% and positioning to fell at 9.5%. The dominance of machine movement along the rack was not anticipated and was in part owing to steep ramps to the forest road at one end of the racks and a soft track at the other.

Given the importance to the research objectives of the harvester work study in the Irregular Tract, many permutations of independent and dependent variables were tested – nearly 50. Ultimately it was seen that separation into two relationships, fully harvested by the harvester and partly harvested by the harvester yielded, the most useful results as shown in Figures 4.8 and 4.9.

Figure 4.8 Harvester (full cycle) Irregular Tract – work rate versus size
The coefficients of determination were impacted by the variable and significant impacts of the harvester movement element of the work cycle. Since the harvester was at times reaching the limits of its capacity, the power function relationship might be expected to yield a better fit to the data.

It is well known that tree species can be a factor in harvesting time consumption. Therefore separate analyses were done for Douglas fir and Western red cedar. Results were mixed with fully harvested Douglas fir and Western red cedar not felled by the harvester displaying worse correlations than the all-species analyses. Figures 4.10 through 4.13 show results for the individual species. It might have been expected that the full cycle harvesting of the cedar would have been less predictable than for the Douglas owing greater variability in form and branchiness; the opposite result was found. However, the processing of cedar not felled by the harvester compared to the Douglas yielded the expected result of better predictability for the Douglas fir for the same reason. As stated previously, movement of the harvester was more variable and consumptive of time than expected and is the likely explanation for lower correlation in results.
Figure 4.10 Harvester (full cycle DF) Irregular Tract – work rate versus size

![Harvester (Full cycle DF) Irregular Tract](image)

\[ y = -151.49x^2 + 115.07x + 276.88 \]
\[ R^2 = 0.495 \]

\[ y = 185.69x^{0.806} \]
\[ R^2 = 0.4646 \]

Figure 4.11 Harvester (full cycle RC) Irregular Tract – work rate versus size

![Harvester (Full cycle RC) Irregular Tract](image)

\[ y = 487.94x^2 - 1307.5x + 1015.4 \]
\[ R^2 = 0.7003 \]

\[ y = 254.57x^{0.548} \]
\[ R^2 = 0.7055 \]
Figure 4.12 Harvester (no fell DF) Irregular Tract – work rate versus size

\[ y = 212.01x^2 - 832.64x + 1021.3 \]

\[ R^2 = 0.7826 \]

Figure 4.13 Harvester (no fell RC) Irregular Tract – work rate versus size

\[ y = 93.412x^2 - 536.01x + 889.93 \]

\[ R^2 = 0.553 \]
4.2.3 Forwarding Irregular Tract

Forwarding in the Irregular Tract required ten trips to recover 404 pieces to the log landing. Distances traveled were low at an average of 148 m on woods trails, 58 m on racks and 60 m on the logging road. Saw logs were initially recovered followed by the small wood. As might be expected in an irregular harvest, there was a large variance in size with a range from 1.54 to 0.07 m³ per piece. Owing to the short distance to the log landing and variety of timber to recover (see Appendix VI for timber specification), only four of ten trips were full loads. The large range in piece size and partial loads did not warrant in-depth statistical analysis. However, elemental time consumption yielded insight into the forwarding performance and correlation between mean piece volume was notable, especially for full loads. Table 4.5 shows the work cycle elemental breakdown similarly to Table 4.3 for the Slope Tract. Only the ‘Travel Loading’ element is materially different from the Slope Tract most likely owing to the impacts of loading off racks versus a hardcore road, though sample size mitigates against being too definitive on that point.

Table 4.5 Forwarder work breakdown structure results Irregular Tract

<table>
<thead>
<tr>
<th>Loads</th>
<th>Travel Empty (%)</th>
<th>Load (%)</th>
<th>Travel Loading (%)</th>
<th>Travel Loaded (%)</th>
<th>Unload (%)</th>
<th>Travel Unloading (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>12.6</td>
<td>28.9</td>
<td>27.0</td>
<td>9.1</td>
<td>22.4</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Correlation with mean piece volume is shown in Figures 4.14 and 4.15 for full loads and all loads, respectively. The correlation appears clear for full loads (though there are only four sample points). Correlations with number of pieces per load and load cycles were also trialled with good correlation for full loads and otherwise poor correlations.
The circa 1.5 m³ volume in Figure 4.15 might be considered an outlier as it represents two large logs of mean volume 1.536 m³. However that is not an outlier data point as it is representative of the nature of the harvest with some logs to recover which are on the limits of the forwarder crane capability. In any event, removing that data point only moves $R^2$ to 0.62.
As with the Slope Tract, winching was a necessary, but small part of the harvesting activity. Three trees in the mid-field required winching into reach of the harvester while eight large logs, average nearly 2.0 m³, required winch recovery to the log landing. Those required only two trips into the stand. Work study data was captured, but not analysed.

4.2.5 Irregular Tract overall productivity and cost results

Table 4.6 shows the overall results for the Irregular Tract. As with the Slope Tract, all volumes were corrected back to the harvester volume, i.e. the overall caliper and tape measurements were adjusted to match the harvester so that the impact of different measurements methods was hopefully minimised. For the Irregular Tract; however, the calipers and tape were only 3.0% high to the harvester. The same methodology was applied for delay factors and calculation of the aggregate total harvest cost.
Table 4.6 Irregular Tract overall results

<table>
<thead>
<tr>
<th>Great Coombe Irregular Tract Harvesting Productivity and Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Volume</strong></td>
</tr>
<tr>
<td>(m³)</td>
</tr>
<tr>
<td>Harvester</td>
</tr>
<tr>
<td>Forwarder</td>
</tr>
<tr>
<td>Winch</td>
</tr>
<tr>
<td>Chainsaw</td>
</tr>
<tr>
<td><strong>TOTAL HARVESTING COSTS</strong></td>
</tr>
</tbody>
</table>

The delay factors during the Irregular Tract study were extraordinary and largely owing to mechanical issues with both the harvester and forwarder. A dead battery, badly worn tire thrown off the rim, electrical problems and an engine water leak were the major contributors. The chainsaw felling delay factor was mostly owing to inefficiencies brought about by limited work to do, but over a period of time. The delays had a major impact on the cost calculation, e.g. a more reasonable delay factor of 30% would have yielded a 28% decrease in aggregate harvesting cost to £19.18 per cubic metre.

4.2.6 Irregular Tract XL Douglas fir harvest

Very large Douglas fir, harvested for structural timbers, are a characteristic of Stourhead. Eight trees, ranging from 105.0 – 118.0 cm and 13.49 – 21.57 m³ in volume were felled during the study and four were recovered to roadside. The remainder were sold but remained on location until the buyer specified the crosscuts – usually to meet a specific order. Time study was done on both the felling and skidder recovery of this timber; however, only the overall productivity was assessed. The largest single stem recovered by the JD 380C skidder was 11.95 m³,
while the average was over 5 m³. By felling this timber after the main harvest, felling lines and ease of extraction were both improved.

There were initial attempts to extract whole tree sections to clear the timber from the forest to roadside where the buyer could access the stems for crosscut on a flexible basis. However, that was unsuccessful, which accounted for a large delay factor. Table 4.7 shows the results for harvesting of the extra-large Douglas fir. The size of the stems made this harvesting extremely productive on a delay free basis.

Table 4.7 Irregular Tract harvesting results for extra-large Douglas fir

<table>
<thead>
<tr>
<th></th>
<th>Volume (m³)</th>
<th>Delay Free Prod. (m³/hr)</th>
<th>Total Prod. (m³/hr)</th>
<th>Delay Factor (%)</th>
<th>Rate per hour (£/hr)</th>
<th>Delay Free Cost (£/m³)</th>
<th>Total Cost (£/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skidder</td>
<td>47.9</td>
<td>31.3</td>
<td>5.3</td>
<td>491.2</td>
<td>75</td>
<td>2.40</td>
<td>14.15</td>
</tr>
<tr>
<td>Chainsaw</td>
<td>47.9</td>
<td>13.1</td>
<td>8.9</td>
<td>47.4</td>
<td>35</td>
<td>2.67</td>
<td>3.93</td>
</tr>
<tr>
<td><strong>TOTAL HARVESTING COSTS XL DOUGLAS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.07</td>
</tr>
</tbody>
</table>

4.3 Winch Tract results

The Winch Tract represents another harvesting scenario at Stourhead, largely dictated by the landscape. That harvesting area had marginally greater average slope than the Slope Tract study area and a longer run from a forest road at the bottom to a forest track on the plateau at the top. Harvester access was not practical and especially for the modest distances involved. So the harvesting scenario was chainsaw felling followed by whole tree winch recovery to the plateau followed by harvester processing and then forwarder recovery to a nearby log landing. A total of 35 mostly Western hemlock (*Tsuga heterophylla*) were felled with mean diameter 30.3 cm.
4.3.1 Chainsaw felling Winch Tract

While this felling was similar to the Slope Tract, walking conditions were more challenging, partly owing the slope but more so the brash yet remaining from the last thinning in 2008. Time study was done in the interest of noting any differences from the Slope Tract, notwithstanding the obvious difference of larger timber in that study area. Figure 4.16 shows the results.

Figure 4.16 Chainsaw felling Winch Tract

The three points furthest to the right were Douglas fir ranging between 44.5 and 52.4 cm DBH. Removing those did not improve the correlation, and in any event they are relevant data.

4.3.2 Winch recovery of whole trees

Thirty of thirty-five trees were winched butt end first up the slope to the plateau, while it was more efficient to winch the remaining five, top first, to the forest road below the slope. Winching distance ranged from 6 metres to 44 metres while the average was only 21.3 metres. Twenty-five winch runs were required, i.e. at times more than one tree was simultaneously being recovered. Snedding was required on two of the larger Douglas fir to reduce friction to the point where the winch had capacity to pull them. While time study data was captured in the event of some
future interest, it was not seen worthwhile to analyse that given the variable nature of the work. The time study did provide the delay factor for use in productivity calculations.

### 4.3.3 Harvester processing Winch Tract

This harvesting was similar to the Slope Tract with the harvester processing trees which had already been felled. The access was different though, a narrow forest trail compared to a reasonable quality haul road for most of the trees. Also the harvester had to ‘nose in’ to reach most of the trees. The harvester processing, based on observation, was quick and efficient. Figures 4.17 – 4.20 show the results with the same graphs as those used for the Slope Tract because one would expect similarities. The correlations of DBH to felling time did remain the better predictor in the Winch Tract though with a lesser coefficient of determination – 0.58 versus 0.76 at the Slope Tract for the quadratic relationship. Stem volume also remained a reasonable predictor of time. Most importantly though, one sees similar productivity for the harvester, e.g. at 30 cm DBH the delay free time is very similar between the two studies which gives some confidence to the results.

Figure 4.17 Harvester processing Winch Tract – time versus DBH
Figure 4.18 Harvester processing Winch Tract – time/volume versus DBH

![Graph showing time/volume relationship with DBH]

- Equation: $y = 0.7647x^2 - 62.573x + 1499.8$
- $R^2 = 0.5048$

Figure 4.19 Harvester processing Winch Tract – time versus size

![Graph showing time versus size relationship]

- $y = 10554x^{-0.028}$
- $R^2 = 0.4718$

- Equation: $y = 12.466x^2 + 144.42x + 100.24$
- $R^2 = 0.5587$

- Equation: $y = 247.41x^{0.4726}$
- $R^2 = 0.4967$
4.3.4 Forwarding Winch Tract

Two full loads were required to recover 50 saw logs and 192 short wood. Again travel distances were short owing to the relatively dense road network at Stourhead. Average distances were 517 metres on the forest road and 130 metres on the forest track. The recovery of timber was much as for the Slope Tract, so for comparability, the results were presented in the same way. Table 4.8 below shows the forwarder’s overall productivity for the operation. The impact of the large amount of small wood, over double that of the Slope Tract is clear to see with productivity less than half that of the Slope Tract.

Table 4.8 Forwarder productivity Winch Tract

<table>
<thead>
<tr>
<th>Load</th>
<th># Pieces</th>
<th>Mean Volume (m³)</th>
<th># Load Cycles</th>
<th>Load Volume (m³)</th>
<th>Time (minutes)</th>
<th>Productivity (m³/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>0.240</td>
<td>23</td>
<td>11.984</td>
<td>59.381</td>
<td>12.1</td>
</tr>
<tr>
<td>2</td>
<td>192</td>
<td>0.084</td>
<td>54</td>
<td>16.167</td>
<td>88.329</td>
<td>11.0</td>
</tr>
<tr>
<td>Total</td>
<td>242</td>
<td>0.116</td>
<td>77</td>
<td>28.151</td>
<td>147.710</td>
<td>11.4</td>
</tr>
</tbody>
</table>
The elemental work breakdown structure results are shown below in Table 4.9, again for direct comparison with the Slope Tract. The main differences relate to the greater, though still moderate, travel distances for the forwarder.

Table 4.9 Forwarder work breakdown structure results Winch Tract

<table>
<thead>
<tr>
<th>Load</th>
<th>Travel Empty (%)</th>
<th>Load (%)</th>
<th>Travel Loading (%)</th>
<th>Travel Loaded (%)</th>
<th>Unload (%)</th>
<th>Travel Unloading</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>29.9</td>
<td>27.9</td>
<td>21.6</td>
<td>3.3</td>
<td>17.3</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>29.3</td>
<td>33.2</td>
<td>14.9</td>
<td>2.9</td>
<td>19.7</td>
<td>0.0</td>
</tr>
<tr>
<td>Average</td>
<td>29.5</td>
<td>31.0</td>
<td>17.6</td>
<td>3.1</td>
<td>18.8</td>
<td>0.0</td>
</tr>
</tbody>
</table>

4.3.5 Winch Tract overall productivity and cost results

Table 4.10 shows the overall results for the Winch Tract. The trees were of moderate size with mean DBH 30.3 cm and mean volume 0.7 m³. All volumes taken by calipers and tape were adjusted to the harvester volume, with the manual method yielding results +4.8% to the harvester. Again delay factors are a function of productive work time and were low during this study. The impact on costs of harvesting larger relative volumes of small wood is clear to see compared to either the Slope Tract or the Irregular Tract. The forwarder was particularly impacted with costs nearly double that of the Slope Tract for almost the same volume handled - 25.4 m³ on the Winch Tract versus 25.7 m³ on the Slope Tract.
4.4 Regular Tract results

The Regular Tract was on ground which had previously been leased to the Forestry Commission and was within a large block of plantation forestry. The area had been planted on 2 metre by 2 metre spacing, with racks established on 20 metre spacing through the removal of one row. The previous thinning had been in 2011. The nearly 2.7 acre study block contained five racks, and 369 stems of mean DBH 16.6 cm, mean size 0.2 m³ were harvested.

4.4.1 Harvester Regular Tract

A smaller harvester than the John Deere 1470D could have been used; however, that would have been impractical for the varied harvesting done at Stourhead. In practice, the harvester was able to manoeuvre on the racks and reach trees to be felled without difficulty. Full time study was done for the harvesting so that data was available for any further comparison of work element performance to the other study tracts at a later date. Ultimately productivity was the main objective and productivity for each rack (lengths 151 metres with little variance) was assessed for use in overall calculations. As shown by Figures 4.21 and 4.22 below, work rate versus DBH and volume both gave reasonably good correlations, though the
correlation to DBH was better, in fact excellent. Little difference was seen between quadratic and power functions. Since the machine was in all respects working well within its capacity, the power function would not be expected to be relevant.

Figure 4.21 Harvester Regular Tract – work rate versus DBH

Figure 4.22 Harvester Regular Tract – time/volume versus size
4.4.2 Forwarding Regular Tract

Forwarding, while subjected to time study, was also analysed at an aggregate level for productivity. Of seven total loads with a total of 1491 pieces, four were full, one two thirds full and the last, half full. The variety of products loaded in different loads rendered analysis on a by-load basis unuseful, so only overall productivity was calculated. Overall descriptive statistics are shown for the forwarding in Table 4.11.

Table 4.11 Forwarder productivity Regular Tract

<table>
<thead>
<tr>
<th>Load</th>
<th># Pieces</th>
<th>Mean Volume</th>
<th># Load Cycles</th>
<th>Total Volume</th>
<th>Time</th>
<th>Productivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1491</td>
<td>0.168</td>
<td>410</td>
<td>55.4</td>
<td>400.632</td>
<td>8.3</td>
</tr>
</tbody>
</table>

It is unsurprising owing to the large number of pieces that the elemental breakdown showed nearly 62% of elapsed time spent loading timber. Traveling time, as for the other study areas, was modest owing to an average forwarding distance by forest road of 480 metres and average rack length of 151 metres. Table 4.12 shows the elemental activity breakdown for the Regular Tract.

Table 4.12 Forwarder work breakdown structure results Regular Tract

<table>
<thead>
<tr>
<th>Load</th>
<th>Travel Empty (%)</th>
<th>Load (%)</th>
<th>Travel Loading (%)</th>
<th>Travel Loaded (%)</th>
<th>Unload (%)</th>
<th>Travel Unloading (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>5.4</td>
<td>47.0</td>
<td>14.8</td>
<td>11.6</td>
<td>21.3</td>
<td>0.0</td>
</tr>
</tbody>
</table>

4.4.3 Regular Tract overall productivity and cost results

Table 4.13 shows the overall results for the Regular Tract. The harvesting and forwarding were without incident. The relatively short racks may have impacted the
the study compared to larger, unbroken expanses of even-aged forestry, however, at nearly three times the racks distances for the Irregular Tract, that means the Regular Tract was advantaged in that respect. Overall costs for this tract were marginally more than for the Winch Tract notwithstanding the manual felling and winch elements of that tract and nearly double that for the Irregular Tract. The impact of tree diameter and volume is clear to see.

Table 4.13 Regular Tract overall results

<table>
<thead>
<tr>
<th>KWW Regular Tract Harvesting Productivity and Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
</tr>
<tr>
<td>(m³)</td>
</tr>
<tr>
<td>Harvester</td>
</tr>
<tr>
<td>Forwarder</td>
</tr>
<tr>
<td><strong>TOTAL HARVESTING COSTS</strong></td>
</tr>
</tbody>
</table>

5 Discussion

5.0 Comparative results at Stourhead (Western) Estate

This research had a primary objective of quantifying harvesting productivities and costs for four different study areas which represented the range of harvesting scenarios seen at Stourhead. Further, it was hoped to establish regression equations for the Irregular Tract which might be used to predict future harvesting costs as the stand structure continues to be developed and managed by single tree selection. The previous section focussed on results by study area while here the comparative results will be discussed.

The four areas differed in stand characteristics, terrain and harvesting methods as identified in Tables 3.2 and 3.3. It is not possible to mathematically compare the four study areas except at the level of cost per cubic metre since each area had a different harvesting process, e.g. Slope Tract – hand fell toward reach of harvester,
process with harvester, forward, and winch to recover a few large logs. However, while conditions in each stand were different, there is value in observing how the most costly elements of harvesting, the harvester and forwarder performed.

5.1 Comparative harvester and forwarder elemental time consumption

Table 5.1 shows comparative elemental time consumption for the harvester for the four study areas. In that comparison, it must be recognised that the harvester did not do the felling in either the Slope or the Winch Tract which mitigates against any direct comparison with stem diameter or volume.

‘Process’ time was consistently the largest element of time consumption. And broadly speaking, the two study areas where harvester felling was not done (Slope and Winch Tracts; circa %56 - 52) and the two where full cycle processing was done (Irregular and Regular Tracts; circa %40 - 35) had consistent results. In all cases, the study areas with the larger volume stems required a greater proportion of time in processing as would be expected.

The ‘Move’ element was normalised by removing all non-harvesting movement, e.g. travel to site. The Slope Tract ‘Move’ time consumption is understandably lower than for the other study areas – a straight run on a hard-core road compared to manoeuvring onto and on racks. For the other three areas, ‘Move’ time was consistently the second largest factor in time consumption. The Winch Tract result will have been impacted by the lack of a felling cycle, rendering the result for ‘Move’ higher than it otherwise would have been. The Irregular Tract had short racks (average 58.1 metres) compared to the Regular Tract (average 151.4 metres) and both had somewhat difficult rack entry access which would have had proportionately more impact on ‘Move’ time for the Irregular Tract. The geometry of the harvesting blocks at Stourhead is at least partly a function of the development of infrastructure at a time when fully mechanised harvesting was not yet well-developed and also a function of road building on slopes along strike with resultant steep entries to the racks.
‘Positioning’ time, positioning the harvester head to fell, required a greater percentage of time in the Regular Tract than in the Irregular Tract, an easily observable function of the density of stems. Brash handling was a minor component for all but the Slope Tract. The result there was impacted by all the brash falling on the road which then required removal back onto the forest floor. Overall the inspection of the elemental breakdown for harvesting shows explainable differences and consistency across the four harvested areas.

Table 5.1 Harvester performance – elemental breakdown

<table>
<thead>
<tr>
<th>Study Area</th>
<th>Move (%)</th>
<th>Position (%)</th>
<th>Fell (%)</th>
<th>Process (%)</th>
<th>Brash (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope Tract</td>
<td>15.3</td>
<td>4.5</td>
<td>0.0</td>
<td>56.2</td>
<td>24.0</td>
</tr>
<tr>
<td>Irregular Tract</td>
<td>39.4</td>
<td>9.2</td>
<td>7.9</td>
<td>39.9</td>
<td>3.6</td>
</tr>
<tr>
<td>Winch Tract</td>
<td>34.5</td>
<td>10.2</td>
<td>0.0</td>
<td>52.3</td>
<td>3.0</td>
</tr>
<tr>
<td>Regular Tract</td>
<td>30.4</td>
<td>14.0</td>
<td>16.6</td>
<td>35.2</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Table 5.2 shows comparative elemental time consumption for the forwarder for the four study areas. The location of the timber stacking area in relation to the harvested area has a large impact on ‘Travel Empty’ and ‘Travel Loaded’ times, so while an imperfect solution, those two elements have been summed in the final column of the table. The further complication with forwarder studies is the variance in loading along rack length and traveling (to and from timber stack) distances. Those are shown in Table 5.3 for the study areas – and are broadly the same for all areas except the Irregular Tract.

The most notable difference in time consumption is for the Regular Tract where the number of pieces handled and density of wood along the rack resulted in a greater proportion of time loading and a lesser proportion of time travelling while loading.
Table 5.2 Forwarder performance – elemental breakdown

<table>
<thead>
<tr>
<th>Study Area</th>
<th>Travel Empty (%)</th>
<th>Load (%)</th>
<th>Travel Loading (%)</th>
<th>Travel Loaded (%)</th>
<th>Unload (%)</th>
<th>Travel Empty + Loaded (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope Tract</td>
<td>12.4</td>
<td>34.5</td>
<td>10.6</td>
<td>15.0</td>
<td>27.5</td>
<td>27.4</td>
</tr>
<tr>
<td>Irregular Tract</td>
<td>12.6</td>
<td>28.9</td>
<td>27.0</td>
<td>9.1</td>
<td>22.4</td>
<td>21.7</td>
</tr>
<tr>
<td>Winch Tract</td>
<td>29.5</td>
<td>31.0</td>
<td>17.6</td>
<td>3.1</td>
<td>18.8</td>
<td>32.6</td>
</tr>
<tr>
<td>Regular Tract</td>
<td>5.4</td>
<td>47.0</td>
<td>14.8</td>
<td>11.6</td>
<td>21.3</td>
<td>17.0</td>
</tr>
</tbody>
</table>

Table 5.3 Forwarder performance – travelling distances

<table>
<thead>
<tr>
<th>Study Area</th>
<th>Loading (m)</th>
<th>Travelling (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slope Tract</td>
<td>132</td>
<td>418</td>
</tr>
<tr>
<td>Irregular Tract</td>
<td>58</td>
<td>266</td>
</tr>
<tr>
<td>Winch Tract</td>
<td>130</td>
<td>517</td>
</tr>
<tr>
<td>Regular Tract</td>
<td>151</td>
<td>480</td>
</tr>
</tbody>
</table>

The inspection of elemental time consumption between the study areas for forwarding again suggests a consistency of results that should give some confidence that the operators performed much in the same way in each study area.

5.1.1 Elemental time consumption comparison with other studies

It is not common to find elemental time consumption results in the literature, and even less so for comparable harvests. It would seem appropriate to consider that information since that can give direct insights to the mechanical performance of the harvesting. Two authors, Ireland (2008) and Jonsson (2015), provided such data in
studies which have at least some level of comparability. The Ireland study was a heavy final thinning (50% of basal area, leaving 20.8 m$^2$/ha) of a Sitka spruce stand wherein the mean harvested tree size was 1.78 m$^3$ with mean DBH 40 cm. The study duration was 7.7 hours delay free. The Jonsson study showed results for harvesting stems of mean size 1.69 m$^3$, no diameter provided, over a period of just over an hour in a tract moving toward an irregular structure. Both studies required some combining of time elements to arrive at comparative values. Ireland had used twelve elements in his work breakdown structure, while Jonsson used seven. The better match to any of the Stourhead harvests was the Irregular Tract (mean size 1.0 m$^3$, mean DBH 42 cm, 4.0 hours delay free time for harvester) so the Ireland and Jonsson results are shown in Table 5.4 in relation to that study. Notable differences occur in ‘Position’ for the Jonsson study and ‘Fell’ for the Ireland study. The high percentage of positioning time in the Jonsson study is not fully understood, but may be related to a conclusion in that study that operators would need training in tree selection, i.e. the operator was not accustomed to self-selecting trees in a selection harvest. Trees had been marked for the harvester operator at Stouhead. The ‘Fell’ difference can be understood in the Ireland work as it was noted that the harvester was under-sized for the work and multiple felling cuts were required at times. While direct comparison is difficult, it is believed this limited comparison adds weight to the reasonableness of the Stourhead results, they are not unexplainably different.

Table 5.4 Irregular Tract harvester elemental comparisons other studies

<table>
<thead>
<tr>
<th>Study Area</th>
<th>Move (%)</th>
<th>Position (%)</th>
<th>Fell (%)</th>
<th>Process (%)</th>
<th>Brash (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irregular Tract</td>
<td>39.4</td>
<td>9.2</td>
<td>7.9</td>
<td>39.9</td>
<td>3.6</td>
</tr>
<tr>
<td>Ireland (2008)</td>
<td>31.8</td>
<td>5.9</td>
<td>20.9</td>
<td>37.0</td>
<td>4.4</td>
</tr>
<tr>
<td>Jonsson (2015)</td>
<td>26.8</td>
<td>19.0</td>
<td>5.9</td>
<td>47.9</td>
<td>0.4</td>
</tr>
</tbody>
</table>
Table 5.5 shows a similar comparison for forwarding. Again it was necessary to combine elements in the Ireland and Jonsson studies. The travelling times have not been aggregated, but caution must be stated – location of the timber stack in relation to the harvest impacts travel empty and loaded times. Forwarding distances for all three studies were about the same so that factor alone should have little impact on the percentage of time taken by travelling. While the geometry of the comparison studies is not known, that of the Irregular Tract meant travel loading time exceeded travel loaded time owing to purposefully selectively loading similar sized/length timber during most forwarder trips, meaning the distance travelled once fully loaded was shortened. The study durations ranged from 9.9 hours for Ireland, 5.4 hours for Stourhead to 0.4 hour for the Jonsson study – all delay free times. As for the harvester, there is reasonable agreement between the elemental work activity time consumption between the three studies.

Table 5.5 Irregular Tract forwarder elemental comparisons other studies

<table>
<thead>
<tr>
<th>Study Area</th>
<th>Travel Empty</th>
<th>Load</th>
<th>Travel Loading</th>
<th>Travel Loaded</th>
<th>Unload</th>
<th>Travelling Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>m</td>
</tr>
<tr>
<td>Irregular Tract</td>
<td>12.6</td>
<td>28.9</td>
<td>27.0</td>
<td>9.1</td>
<td>22.4</td>
<td>266</td>
</tr>
<tr>
<td>Ireland (2008)</td>
<td>16.2</td>
<td>30.8</td>
<td>15.7</td>
<td>18.9</td>
<td>18.4</td>
<td>187</td>
</tr>
<tr>
<td>Jonsson (2015)</td>
<td>12.6</td>
<td>32.8</td>
<td>13.8</td>
<td>13.3</td>
<td>27.5</td>
<td>220</td>
</tr>
</tbody>
</table>

5.2 Comparative harvester and forwarder productivities

The nature of the harvests at Stourhead, other than in the Regular Tract, required supporting harvesting activities to the harvester and forwarder. Therefore, comparison of harvesting productivities between the different stands/harvesting methods cannot be meaningfully done at an aggregate volume per hour basis. However, it is instructive to view the comparative performances of the harvesting and forwarding since those are by far the most costly elements of the harvesting. Table 5.6 provides some overall descriptive statistics for the harvests. The scale of
the studies was purposefully larger for the Irregular Tract as that one was of primary interest to develop predictive relationships for future harvesting operations.

The most notable variance for the harvester is for the Regular Tract where productivity is less than half that for the other tracts. That demonstrates the relationship found by many researchers, e.g. Nurminen et al (2006) and Eriksson and Lindroos (2014) that harvesting productivity increases with stem diameter and size. However, the harvester productivity in the Regular Tract appears to be half that found by Nurminen et al in their work for that mean stem size. Their study, though, was focussed mostly on final fellings with a limited sample of thinnings. The harvesting productivity was lower than, but more in line with that found by Eriksson and Lindroos. They noted that though mean tree size was the largest influence on harvesting productivity, difficult trees, terrain and the bucked assortment and other variables impacted as well. In any event it is believed that the within forest comparisons represented by the Stourhead study, using the same men and equipment yielded results which were appropriate comparisons of the harvesting techniques under identified stand and site characteristics.

Forwarder productivity appeared well-matched to harvester productivity for the Slope and Regular Tracts in particular. As with the harvester, the lower productivity at the Regular Tract was in line with the large numbers of small pieces handled and similar was experienced at the Winch Tract. As stated by Nurminen et al (2006), the factors affecting forwarder performance in addition to piece size are many including wood density on the rack, harvester operator proficiency in stacking and assortment cut. On the latter, productivity was seen to suffer on the Winch Tract owing to two timber specs of little variance in length (0.1 metre) such that the operator had to re-sort the load with some frequency to have the correct timber in the correct stack.
5.2.1 Comparative harvester and forwarder productivities for Irregular Tract

The Irregular Tract was of particular interest in this research and it was previously noted that only two broadly comparable and recent studies were found. The similarities and differences for time consumption were discussed in 5.1.1. Table 5.7 shows Stourhead productivity results compared to those of Ireland (2008) and Jonsson (2015). Those are only partial comparisons because further means of harvesting were used at Stourhead, namely chainsaw felling and limited winch extraction. In any event, there appears to be reasonable agreement with the study of Jonsson (2015). With regard to Ireland (2008) the harvester productivity is much greater and the forwarder calculation methodology is different. It is believed the greater harvesting productivity is answered by considering the nature of the felling by Ireland, a penultimate thinning in a conversion to CCF. That thinning was over 50% of basal area, leaving a basal area of 20.8 m²/ha. The Stourhead harvest was a selection harvest of 20% of basal areas leaving a basal area of 31.6 m²/ha. The intensity of harvest, along with the larger average stem size should be expected to yield greater productivity. Regardless, it is believed there is some validation of the Stourhead results by these comparisons. Further notwithstanding the Bacher (2003) study was earlier and used a tracked harvester, the similarities to the Irregular Tract harvesting methodology were very good, and her work guided the harvesting design for the Irregular Tract. At the highest level of results, for average DBH 49 cm, the

---

**Table 5.6 Overall harvesting productivity**

<table>
<thead>
<tr>
<th>Study Area</th>
<th>Delay Free Time</th>
<th>Volume</th>
<th>Harvester Prod.</th>
<th>Forwarder Prod.</th>
<th>Mean DBH</th>
<th>Mean Stem Size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hours</td>
<td>m³</td>
<td>m³/hr</td>
<td>m³/hr</td>
<td>cm</td>
<td>m³</td>
</tr>
<tr>
<td>Slope Tract</td>
<td>4.9</td>
<td>30.0</td>
<td>20.4</td>
<td>21.6</td>
<td>47.0</td>
<td>1.8</td>
</tr>
<tr>
<td>Irregular Tract</td>
<td>17.7</td>
<td>96.5</td>
<td>20.2</td>
<td>15.1</td>
<td>42.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Winch Tract</td>
<td>8.4</td>
<td>25.4</td>
<td>17.1</td>
<td>10.3</td>
<td>30.3</td>
<td>0.7</td>
</tr>
<tr>
<td>Regular Tract</td>
<td>13.1</td>
<td>55.4</td>
<td>8.6</td>
<td>8.3</td>
<td>16.6</td>
<td>0.2</td>
</tr>
</tbody>
</table>

---
Bacher work showed 22 m³/hour for the harvester and 27 m³/hr for the forwarder, again giving some confidence to the Stourhead results.

Table 5.7 Irregular Tract harvesting productivity comparisons

<table>
<thead>
<tr>
<th>Study Area</th>
<th>Harvester Prod. m³/hr</th>
<th>Forwarder Prod. m³/hr</th>
<th>Mean DBH cm</th>
<th>Mean Stem Size m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irregular Tract</td>
<td>20.2</td>
<td>21.6</td>
<td>42.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Ireland (2008)</td>
<td>47.5</td>
<td>&gt; 25.0</td>
<td>40.0</td>
<td>1.8</td>
</tr>
<tr>
<td>Jonsson (2015)</td>
<td>17.1</td>
<td>17.6</td>
<td>NA</td>
<td>1.7</td>
</tr>
</tbody>
</table>

5.3 Irregular Tract regression equations

The results for the Irregular Tract were presented in section 4.2. An objective of this research was development of regression equations which might be used to predict harvesting costs for future interventions. Regression equations were developed for three of the four techniques used in the harvesting: chainsaw, harvester and forwarder.

The chainsaw equation in Figure 4.7 could be used for future predictions and has reasonable coefficients of determination; however, it is thought possible to estimate that element closely enough based on the time element of chainsaw harvesting in proportion to the volume harvested since in any event that is a small element of overall costs. That is apparent when one considers only 6.4 hours of chainsaw work was required in a total harvest of 96.5 m³.

Regressions were done for the harvester in the same manner as previous researchers, e.g. Nurminen et al (2006) or Price, M. (2007). Relationship were tested between time consumption or work rate as a function of stem diameter or size. Work rate (centiminutes/m³) as a function of stem size in all cases gave better results for the Irregular Tract. The analysis was complicated by different species and the fact that for many stems the harvester did not do the felling. The analyses which neglected species variation and only considered the work done by the harvester
(Figures 4.8 and 4.9) gave coefficients of determination less good (range of 0.65 to 0.75) than those shown by Price, M. (2007) or Nurminen et al (2006), but still in a respectable range. The results by species yielded mixed results. The number of examples and variability of those most likely had an impact on those results. It may be expected the variable nature of the selection harvest in the Irregular Tract might lead to lesser coefficients of determination.

The forwarder regression analysis was more limited (Figures 4.14 and 4.15) owing the scale of the study and level at which the analysis was done – full loads of the forwarder. That yielded a good correlation with mean piece volume, though one should be cautious with the result in view of the limits of the data.

5.4 Comparative costs of harvesting at Stourhead

Table 5.8 shows a compilation of the overall delay free harvesting costs for the four study areas at Stourhead. Other key data is included for ease of reference. The methodology for cost rates for the harvesting equipment was presented in 3.3. Those are believed reasonable, though fully loaded. The same costs were used for all studies, so the relative cost relationships would be little impacted by e.g. assuming the lower costs of used machinery.

The costs per unit volume of course follow the productivity results and further, they provide a mechanism by which the cost implications of harvesting measures additional to the harvester and forwarder may be included. Each item of equipment was included in the final costing only to the extent of its proportionate use on the volume harvested.

The relationship of cost to productivity, hence mean volume and DBH, is clear to see with those study areas containing the larger timber having lower harvesting costs. It is also apparent that the Winch Tract, which required use of a third mechanism (winch) on all of the volume, had a cost penalty that increased costs in that area to nearly those of the Regular Tract.

The Irregular Tract harvesting cost (which is exclusive of the very low cost of harvesting the extra-large Douglas fir) was not much more than half the cost of the
third thinning in the Regular Tract. Notwithstanding the additional harvesting requirements of hand-felling and a moderate amount of winching, the cost per unit volume compared favourably to the other tracts.

Table 5.8 Overall harvesting cost and productivity

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<tr>
<th>Study Area</th>
<th>Delay Free Cost £/m³</th>
<th>Delay Free Time Hours</th>
<th>Volume m³</th>
<th>Harvester Prod. m³/hr</th>
<th>Forwarder Prod. m³/hr</th>
<th>Mean DBH cm</th>
<th>Mean Stem Size m³</th>
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5.5 Limitations and recommendations for further work

It is believed the research achieved the objectives of evaluating harvesting costs across the range of scenarios at Stourhead and developing regression equations that can be used in future economic assessments as more areas of Stourhead develop irregular structures. However, harvesting studies are typically limited by the manpower requirement to both do them and then analyse the data. That means sample size is limited for practical reasons. Notwithstanding the sample sizes were as large, or larger, than many studies, the results by no means can be treated as exact. Particularly for the Irregular Tract, it would be informative to at least monitor gross productivity over a future harvest in another irregular stand at Stourhead. Ideally that could be organised to take full advantage of the StanForD stem files of a suitably equipped harvester run by an operator interested in using the full capabilities of that data system. Strandgard et al (2013) evaluated that approach with acceptable results and commented the lack of an observer avoided the ‘Hawthorne effect’ notwithstanding the disadvantage of lack of physical observations to address apparently anomalous data.
The researcher in this case had not previously done a harvesting study, though familiar with operating and maintaining heavy industrial equipment for many years. It is believed the time study raw data was obtained and recorded with a wholly acceptable level of accuracy. Nuutinen et al (2008) studied the difference between students and professionals in time study work. Professionals had smaller variance of measurement errors than students; however, there were no statistically significant differences in error averages. A mitigating factor as well was that on the advice of very experienced forestry time study researchers, the elemental work breakdown structure was limited to a low number of critical observations. It is hard to see the value of expanded work breakdown structures unless in pursuit of machine or operator improvement at a highly detailed level, which was not an objective of this work.

Delay factors were variable during the study, particularly with the Irregular Tract. Based on observation, it is not thought delay factors were at all related to the stand structures. It is believed the delay free scenarios represented the better bases for comparison, though the inefficiencies occasioned by the delays should not be under-estimated, particularly in terms of harvest planning and economic viability of the harvesting company. Particularly in scenarios such as Stourhead, where operators are paid for output, the operators should recognise the large penalty caused by delay and seek to avoid the majority of that associated with on-the-job unplanned maintenance.

The study benefited, from an internal comparability perspective, in having the same operators and equipment deployed throughout. The impact of operators on productivity has been researched by Ovaskainen et al (2004) and Purfürst (2010) among others. Ovaskainen et al noted up to 40% variability between operators in similar stands while Purfürst found a learning curve impact of 24% loss on average productivity over the first eight months of training and a twenty day learning period to reach plateau productivity when switching to a different harvester. It cannot be said what impact the operators had on productivity during the study, except that their performance appeared consistent throughout. Based on observation and knowledge the harvester operator was less than a year on the harvester after
transferring from forwarding while the forwarder operator was well-experienced, it may be the harvesting rates were lower than a more experienced operator while the forwarder rate would be in the expected range for an experienced operator. The opportunity to evaluate performance of different operators at Stourhead is limited; however, that is a parameter worth monitoring and which again could be relatively simply done with StanForD stem files.

6 Conclusion

The work study at Stourhead provided an opportunity to study four different harvesting scenarios in conifer stands of differing structures. In particular, the opportunity to study harvesting in a well-developed irregular stand alongside that in a nearby regular stand was unique. The results were in line with the general trend identified by previous researchers that productivity increases with stem diameter and volume. This study took the results beyond productivity to costs, and notwithstanding the need for harvesting means in addition to the harvester and forwarder in three of the study areas, costs still followed the general trend of productivity owing to the modest use of and costs associated with those additional harvesting means.

It is recognised that this study provided a set of data associated with the specific conditions at Stourhead, and that particularly for the Irregular Tract, there are no truly comparable harvesting studies. The work of Hiesl & Benjamin (2013) matches this author’s assessment of the caution one should take in extrapolating results from productivity studies. However, efforts were made to use descriptive statistics to reflect the work as transparently as possible such that future work might test the results shown here. It should be emphasised that Stourhead is primarily managed by the selection system, and that should not be confused, e.g. with the CCF approach researched by Ireland (2008, 2009) which ultimately reduced the basal area to a very low figure once regeneration has been established. If one can achieve the type of stable structure as discussed in Zingg et al (1999), then repetitive future harvests at Stourhead may be similar to those in this work, or at least not differ by a wide margin. Through active management, the forests Zingg evaluated
demonstrated the ability to have irregular stand stability over long periods of time and it is not seen why Stourhead should be different.

There can be no doubt the increasing interest in alternatives to even-aged, clear-fell silviculture. It is notable that research on alternatives, including uneven-aged stands, is active in countries which have long been known for plantation silviculture, e.g. Norway with Pukkala et al (2010), Finland with Tahvonen (2011) and of course the UK with Helliwell & Wilson (2012) and the important work of Davies & Kerr (2015). The recent publication by Manning & Walmsley (2018) of a bibliography of technical papers on Continuous Cover Forestry contains over 130 titles published since 2011. As noted earlier in this manuscript, concerns with harvesting costs associated with the alternatives to even-aged silviculture have been among the potential reasons for slow adoption of those alternatives. Costs are only one of the decision factors when considering alternatives; however, at least in the particular circumstances of the selection system at Stourhead, it is hoped this work may give both confidence to the current management system as a viable alternative and also data which can support broader economic analysis of the irregular system. Deffee (2014) established the viability of the AFI abbreviated inventory method for efficiently determining increment. The two works together provide a good working platform on which to base economic analyses of the selection system at Stourhead.

Beyond the work study output and metrics, it is believed there was value in the observational nature of the work. While the forest road network at Stourhead is historic and linked to amenity use, it could be seen that system at times impeded the efficiency of mechanised harvesting. Whether that is practical to address is beyond the scope of this study; however, it would seem possible to at minimum improve rack entry and exit points to achieve efficiencies in the movement element of cycle time especially for the harvester.
7 References


## Appendix I - Chainsaw elemental work breakdown structure

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R – required NVA

N – NVA

A – avoidable NVA

U – unavoidable NVA
**Appendix II – Harvester elemental work breakdown structure**

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R – required NVA

N – NVA

A – avoidable NVA

U – unavoidable NVA
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- **R** – required NVA
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<td>Unexpected</td>
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</table>

R – required NVA

N – NVA

A – avoidable NVA

U – unavoidable NVA
# Appendix VI – Great Combe Timber Specification

<table>
<thead>
<tr>
<th>Product</th>
<th>Sawlogs</th>
<th>Mini logs</th>
<th>Chips (flat grades)</th>
<th>Hardened Sawlogs</th>
<th>Firewood</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Species: (if more than 1 species on a line, can mix in stack)</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Mode</td>
<td>Lengths (ft - in)</td>
<td>Diameter</td>
<td>Season back</td>
<td></td>
</tr>
<tr>
<td>Douglas</td>
<td>1</td>
<td>12 ft 6 in</td>
<td>&gt; 30 ft</td>
<td>11Aug &amp; 15Dec</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6 ft 0 in</td>
<td>&gt; 60 in</td>
<td>11Aug &amp; 15Dec</td>
<td></td>
</tr>
<tr>
<td>Spruce (but not to be perfectly timbered)</td>
<td>1</td>
<td>11 ft 6 in</td>
<td>&gt; 30 in</td>
<td>15Aug &amp; 30Nov</td>
<td></td>
</tr>
<tr>
<td>Spruce (but not to be perfectly timbered)</td>
<td>2</td>
<td>6 ft 0 in</td>
<td>&gt; 60 in</td>
<td>15Aug &amp; 30Nov</td>
<td></td>
</tr>
<tr>
<td>Douglas</td>
<td>2</td>
<td>12 ft 6 in</td>
<td>&gt; 30 in</td>
<td>15Aug &amp; 30Nov</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6 ft 0 in</td>
<td>&gt; 60 in</td>
<td>15Aug &amp; 30Nov</td>
<td></td>
</tr>
<tr>
<td>Larch</td>
<td>1</td>
<td>7 ft 0 in</td>
<td>&gt; 30 in</td>
<td>15Aug &amp; 30Nov</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3 ft 6 in</td>
<td>&gt; 30 in</td>
<td>15Aug &amp; 30Nov</td>
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<tr>
<td>Cedar</td>
<td>1</td>
<td>Maximum</td>
<td>&gt; 60 in</td>
<td>15Aug &amp; 30Nov</td>
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</tr>
<tr>
<td></td>
<td>2</td>
<td>6 ft 0 in</td>
<td>&gt; 60 in</td>
<td>15Aug &amp; 30Nov</td>
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</tr>
<tr>
<td>Larch, Douglas</td>
<td>1</td>
<td>5 ft 0 in</td>
<td>&gt; 60 in</td>
<td>15Aug &amp; 30Nov</td>
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</tr>
<tr>
<td></td>
<td>2</td>
<td>2 ft 6 in</td>
<td>&gt; 60 in</td>
<td>15Aug &amp; 30Nov</td>
<td></td>
</tr>
<tr>
<td>Hemlock, Silver fir, Grand fir</td>
<td>1</td>
<td>2 ft 6 in</td>
<td>&gt; 60 in</td>
<td>15Aug &amp; 30Nov</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2 ft 6 in</td>
<td>&gt; 60 in</td>
<td>15Aug &amp; 30Nov</td>
<td></td>
</tr>
<tr>
<td>Cedar</td>
<td>1</td>
<td>1-2 ft 6 in</td>
<td>&gt; 60 in</td>
<td>15Aug &amp; 30Nov</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1-2 ft 6 in</td>
<td>&gt; 60 in</td>
<td>15Aug &amp; 30Nov</td>
<td></td>
</tr>
<tr>
<td>Cypress</td>
<td>1</td>
<td>2 ft 6 in</td>
<td>&gt; 60 in</td>
<td>15Aug &amp; 30Nov</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2 ft 6 in</td>
<td>&gt; 60 in</td>
<td>15Aug &amp; 30Nov</td>
<td></td>
</tr>
<tr>
<td>Mixed Conifer (ie. cypress, cypress)</td>
<td>1</td>
<td>2 ft 6 in</td>
<td>&gt; 60 in</td>
<td>15Aug &amp; 30Nov</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2 ft 6 in</td>
<td>&gt; 60 in</td>
<td>15Aug &amp; 30Nov</td>
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</tr>
</tbody>
</table>

**Chips (flat grades):**

- Mixed Conifer (ie. cypress, cypress & mixed rough sawn)
- Maximum length: 12 ft (3.6 m)
- Minimum thickness: 1 in (25 mm)
- Season back: 15Aug & 30Nov

**Hardened Sawlogs:**

- Various
- Maximum length: 12 ft (3.6 m)
- Minimum thickness: 1 in (25 mm)
- Season back: 15Aug & 30Nov

**Firewood:**

- Mixed hardwood
- Length: 7 ft (2.1 m)
- Season back: 15Aug & 30Nov

- Mixed hardwood
- Length: 5 ft (1.5 m)
- Season back: 15Aug & 30Nov