Fuel Pellet Production from Reed Canary Grass

Supply Potentials and Process Technology

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Abstract

This thesis focuses on two main areas: methods for assessing regional supply potentials of reed canary grass (*Phalaris arundinacea* L.) (RCG); and process technology for the production of high-quality RCG pellets.

Partial equilibrium modelling, incorporating a break-even price approach, was used to examine supply potentials for RCG in Västerbotten County, northern Sweden. A remote sensing method, using black and white orthophoto interpretation, was developed, by which abandoned fields with low preparation costs (on average 173 SEK $(ha)^{-1}$) could be distinguished from fields with high preparation costs (on average 3990 SEK $(ha)^{-1}$). Based on the assumptions made, RCG production would predominantly be viable in the coastal area of Västerbotten County, and production equal to 1.3 TWh could be supplied at a farmgate fuel price of 116 SEK $MW^{-1}h^{-1}$.

Pelletizing RCG allows it to be transported, stored and handled more easily. To determine the optimum conditions for RCG pelletizing, experiments were performed in an experimental design incorporating the factors: moisture content, steam addition, raw material density, and die temperature. Pre-compaction of the raw material was an efficient method for avoiding uneven pellet production. Through multiple response optimization, process settings were identified for the production of RCG pellets with a bulk density $\geq$ 650 kg m^{-3} and a durability $\geq$ 97.5%. To clarify the underlying mechanisms in the pelletizing process, the influences of moisture content and normal stress on the kinematic wall friction properties of RCG powder were studied. A steep increase in the kinematic wall friction with increasing normal stress was found in the normal stress interval 50-150 MPa. Multiple linear regression modelling of kinematic wall friction measurements at high normal stresses (65 to 376 MPa) revealed a local maximum at moisture contents of 13–16% and normal stresses of 150–225 MPa. Kinematic wall friction and pellet durability maxima occurred in overlapping moisture content ranges; it was, therefore, hypothesised that the two properties were correlated.

Keywords: Phalaris arundinacea; energy crop; bioenergy; abandoned farmland; GIS; durability; bulk density; moisture content; friction

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Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Larsson, S. & Nilsson, C. (2005). A remote sensing methodology to assess the costs of preparing abandoned farmland for energy crop cultivation in northern Sweden. *Biomass and Bioenergy* 28(1), 1-6.

II Larsson, S. (2006). Supply curves of reed canary grass (*Phalaris arundinacea* L.) in Västerbotten County, northern Sweden, under different EU subsidy schemes. *Biomass and Bioenergy* 30(1), 28-37.

III Larsson, S.H., Thyrel, M., Geladi, P. & Lestander, T.A. (2008). High quality biofuel pellet production from pre-compacted low density raw materials. *Bioresource Technology* 99(15), 7176-7182.

IV Larsson, S.H. Kinematic wall friction properties of reed canary grass powder at high and low normal stresses. (submitted)

Papers I-III are reproduced with the permission of the publishers.

1 Introduction

> Renewable energy is derived from natural processes that are replenished constantly. In its various forms, it derives directly from the sun, or from heat generated deep within the earth. Included in the definition is electricity and heat generated from solar, wind, ocean, hydropower, biomass, geothermal resources, and biofuels and hydrogen derived from renewable resources. (IEA, 2002).

During the past 550 million years, organic matter derived from net global photosynthesis has been deposited and transformed into fossil fuels, such as oil, gas, and coal (Berner, 2003). Since 1888, the global carbon fossilisation rate has been exceeded by the utilisation rate, and the amount of ancient photosynthetic matter needed to generate the fossil fuels burned in 1997 was equivalent to 422 times the amount of carbon fossilised globally each year (Dukes, 2003). The use of fossil fuels has become unsustainable and, as a consequence, carbon that was previously bound up within them is being emitted into the atmosphere in the form of carbon dioxide (CO_2). The global atmospheric concentration of CO_2 has increased from a pre-industrial value of 280 ppm in 1750 to 379 ppm in 2005, and the Intergovernmental Panel on Climate Change has stated that "most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic GHG[1] concentrations" (IPCC, 2007).

Depending on underlying assumptions, biomass could potentially contribute 100 to 400 EJ $(yr)^{-1}$ to global energy supply (Berndes *et al.*, 2003)[2]. Combustion of biomass also causes CO_2 emissions, but is considered

[1] green house gases: CO_2, CH_4, N_2O, and halocarbons
[2] 1 EJ = 278 TWh

to be climate neutral since the CO_2 emitted will be incorporated into growing biomass within a relatively short time.

In 2005, the total primary energy supply of the world amounted to 479 EJ. Renewable energy sources constituted 13% and the major part came from biomass and wastes (IEA, 2007) (Figure 1).

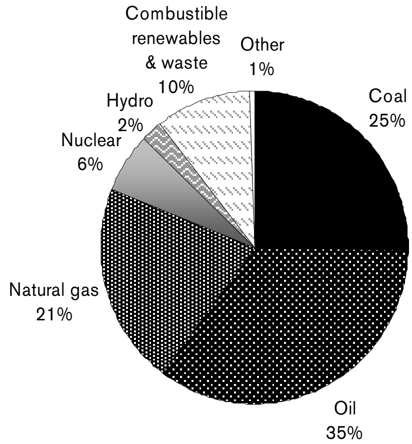

Figure 1. Contribution of different fuels to the primary energy supply of the world in 2005. "Combustible renewables and waste": biomass and animal products, municipal waste, and industrial waste, "Other": geothermal, solar, wind, tide, and wave energy (IEA, 2007).

1.1 Biomass and bioenergy

Biomass is the main renewable energy source (IEA, 2007). Since the beginning of civilization, humans have used biomass as an energy source for cooking and heating. Biomass provides, on average, one-third of the energy needs in Africa, Asia, and Latin America, and as much as 80 to 90% in the least developed countries within these regions (D'Apote, 1998). In Sweden, 19% (116 TWh) of the energy supply in the year 2006 came from biomass (Anonymous, 2007b). The main advantages of bioenergy compared to other renewable resources are:

- The energy is stored in physical materials that are safe to handle, store, and transport
- The energy can be extracted at any time without advanced technological systems

1.1.1 Biomass types

Plant biomass can be divided into three main biological types: woody plants, herbaceous plants/grasses, and aquatic plants. Bioenergy resources are either strictly produced for bioenergy purposes or generated as bi-products of other processes.

Today, most bioenergy is produced from the residues of traditional agriculture and forestry, but several studies on the long-term contribution of biomass to future global energy supply highlight dedicated energy cropping as the major potential for increasing this supply (e.g. Berndes *et al.*, 2003; Smeets *et al.*, 2007).

1.1.2 Energy crops

Energy crops are versatile and can be converted into a range of products. Many crop species are multipurpose in that they can be used to produce more than one type of product (e.g. food, feed, fibre, energy). Energy crops can be divided into: cellulose and solid biomass crops (short rotation forest species, cereal straw, herbaceous energy crops, etc.), oil crops (rapeseed, hemp, olive, etc.), and starch and sugar crops (cereals, potato, sugarcane etc.).

Characteristics of the ideal energy crop are high yield, low energy input, low production costs, low nutrient requirements, and a composition with low amounts of contaminants (McKendry, 2002). Furthermore, the desired characteristics depend on local climate, soil conditions, and access to water.

In Sweden, the cold climate limits the number of viable, high-yielding energy crop species. Energy crops are mainly used in solid fuel combustion (spruce, pine, willow, poplar, straw, reed canary grass, and cereal kernels). Cereals are cultivated for fermentation and ethanol production, rapeseed is used for biodiesel production, and various agricultural products are used for the production of biogas (Anonymous, 2007a).

Reed canary grass (*Phalaris arundinacea* L.) (RCG) is one of the best suited energy crops for cold climates (e.g. Lewandowski *et al.*, 2003). In field trials, yield levels of well-established delayed harvested (harvested in spring) RCG were higher in northern Sweden than in southern Sweden, and reached an annual harvest level of 8-9 tonnes dry mass $(ha)^{-1}$ (Landström *et al.*, 1996). Lower yield levels in southern Sweden were explained by higher winter losses resulting from warmer conditions and more rain. Full scale trials in northern Sweden yielded 4-6 DM ton $(ha)^{-1}$ from delayed harvested fields (Larsson *et al.*, 2006). Lower yield levels at full scale production were considered to be due to high harvesting losses.

1.2 Land use and supply potentials

Net primary production of biomass provides essential natural resources such as food, fuel, fibre and shelter. Each year, about 40% of the present net primary production in terrestrial ecosystems is used by humans (Vitousek *et al.*, 1986). Since urbanization began, the priority list of different human land uses has been as follows (Haber, 2007):

- Acquisition and production of food (crop and livestock farming)
- Acquisition and production of non-food items of biological origin (fibres, wood, timber, fuel)
- Building land (for settlements, workshops, transport systems)
- Extraction of non-living materials (quarries, clay pits, mines) and deposition of waste

With the emergence of environmental concerns in the second half of the 20th century, the four main land uses were complemented by two additional ones: recreation and pleasure, and conservation and protection of nature.

Energy and land use are closely intertwined. On the whole, energy production from renewable resources uses much greater areas of land per energy unit than fossil fuels (Table 1).

Table 1. *Land use comparison of different energy supply technologies (Nathwani et al., 1992)*

Energy technology	Land use index*
Biomass	2560
Wind turbines	990
Hydroelectric	760
Solar photovoltaic	63
Coal	3.5
Oil	2
Natural gas	2
Nuclear	1

* In comparison to nuclear power set to a value of 1 in a lifecycle analysis scenario with different assumptions for electric power production.

1.2.1 Determination of biomass supply potentials

The relatively low land use efficiency associated with biomass-based energy production highlights supply potential as an important issue. Smeets *et al.* (2007) define five different types of bioenergy potential:

- Theoretical potential
- Geographical potential
- Technical potential
- Economic potential
- Implementation potential

Theoretical potential defines the upper limit and includes production from land, rivers, seas, and oceans, whereas geographical potential is restricted to terrestrial production. These different potentials have physical constraints that are not subject to major changes over time. Technical potential is defined as the fraction of the geographical potential not used for food production, buildings, etc., and is thus limited by land-use demands from other activities, demands that will change over time. Laws and regulations also limit the technical potential. Non-profitable sources are excluded from the economic potential. Thus, policy decisions at the society level, relating to subsidies and taxes, alter the economic potential. The difference between economic and implementation potentials is explained by institutional factors, also referred to as transaction costs[3].

In a strictly economic sense, the term potential corresponds to a supply curve (supply as a function of price). Actual supply (and demand) is the result of intersecting supply and demand curves (demand as a function of price). However, most studies focus on either the supply side or the demand side. Two general assessment approaches can be identified: demand-driven and resource-focused assessments (Berndes *et al.*, 2003).

The demand-driven assessments focus on the competitiveness of bioenergy or estimate the amount of biomass required to meet specific targets, e.g. environmental issues. Resource-focused assessments evaluate the total bioenergy resource base and competition between different uses of resources, e.g. for land-use optimization.

Assessment of economic potential requires a suitable approach to price-formation of the commodity under consideration. In theoretical microeconomics, there are two major branches for explaining the behaviour of supply, demand and prices: partial and general equilibrium analyses (Samuelson, 1982). Within the partial equilibrium approach, the effects of

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[3] **transaction costs** "A catchall for heterogeneous costs that arise in economic activity. In many deals, parties have to find each other, communicate, measure and inspect the goods that are to be purchased, draw up the contract using lawyers, keep records, and so on. In some cases, compliance needs to be enforced through legal action. All these entail costs in terms of real resources and time, termed *transaction costs*. The reality of these costs contrasts with the frequent assumption of a perfectly clearing, frictionless market" (Oxford Reference Online, 2002).

changes in supply and demand on the equilibrium price and quantity of a particular good are isolated from the rest of the economy. This contrasts with general equilibrium analysis, in which repercussions of changes in any one market throughout the rest of the economy are taken into account. Partial equilibrium analysis is most useful when events in the sector studied have only small effects on the rest of the economy. Also, this method requires less computational resources than general equilibrium analysis.

Paper II provides an example of a resource-focused assessment of the economic potential of energy crop production, where the theoretical and geographical potential is limited to the region of Västerbotten County in northern Sweden. By excluding farmland that is dedicated over the long-term to a specific land-use, the technical potential for energy cropping was evaluated. A partial equilibrium model was created for the economic potential under three different agricultural policy scenarios: two different schemes within the EU's Common Agricultural Policy (CAP) and a third scenario without subsidies.

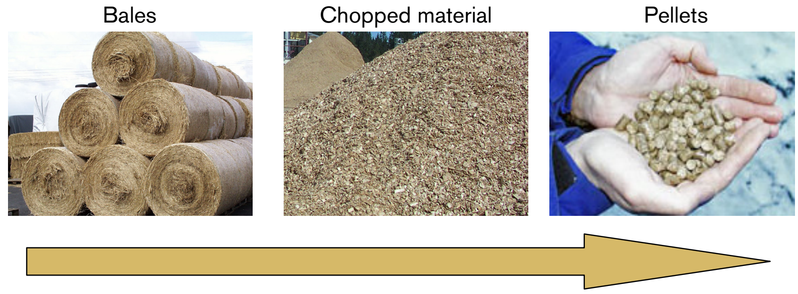
1.2.2 Spatial analysis of biomass supply potentials

Spatial distribution of biomass potentials is highly relevant within production chain analysis of different bioenergy sources. Geographical Information Systems (GIS) provide tools for capturing, storing, analyzing and managing data within their geographical frameworks. Thus, GIS has become a widespread tool in biomass system analysis. GIS tools were used for the work described in both Papers I and II. Combining digital aerial photos and GIS-layers was crucial for Paper I, and manipulating the attribute database, allowing the compilation and transformation of vector data to grid data, thus enhancing visualization of the results, was an important part of Paper II.

1.3 Supply chain efficiency

High efficiency is desirable throughout the whole bioenergy system. As a result of the lower energy density and material losses during storage (especially for non-dried biomass), transport, storage and handling of biomass are more cost and energy intensive than for fossil fuels.

The use of solid biofuels is currently limited to specific markets characterised by the supply of biomass, with more or less clearly defined fuel characteristics, and consumers with different fuel requirements. (Figure 2).



Decreasing
- Transportation expenditure
- Variations in the fuel properties
- Sensitivity during storage
- Technical effort required for conversion

Increasing
- Technical effort to produce the fuel
- Mechanisation
- Output of the fuel producer
- Geographical extent of fuel trading
- Applicability for large scale application

Figure 2. Technical, economic, logistic, and market-related consequences of solid biofuel upgrading (revised from Kaltschmitt & Weber, 2006). The arrow indicates an increasing level of upgrading, and a decreasing variation in fuel properties.

For dry energy crops, such as delayed harvested RCG and straw, the main characteristic that needs to be changed in order to reach a larger market is the bulk volume. This characteristic exhibits a linear relationship with transport and storage costs and affects the size of handling systems and processing equipment in the end-use facilities. The bulk volume of straw and RCG can be reduced substantially by compaction and particle size reduction (Figure 3).

Even in short transport and handling chains, chopping and baling of RCG and straw is necessary. Square or round bales are the most common forms in which straw materials are traded on fuel markets. Even so, the bulk volume of bales restricts the trading area; from practical experiences in Ostrobothnia in Finland, for example, the maximum transport distance for RCG bale deliveries to power plants whilst maintaining profitability is 80 km (Pahkala *et al.*, 2008).

Wafering, briquetting, or pelletizing, are ways to further reduce bulk volume. The bulk volume reduction from round bales to pellets is ten-fold, and hence, the energy investment associated with the mechanical work involved in the compaction processes can be more than regained in reduced storage and transportation costs. In addition, wafers, briquettes, and especially pellets, have advantageous bulk properties and can be handled rationally in transport, storage, loading, feeding systems, etc. The superior bulk properties of pellets compared to wafers and briquettes are probably the main reason why pellets dominate the solid biofuel market and have become a commodity, traded world-wide (Hamelinck *et al.*, 2005; Zwart *et al.*, 2006).

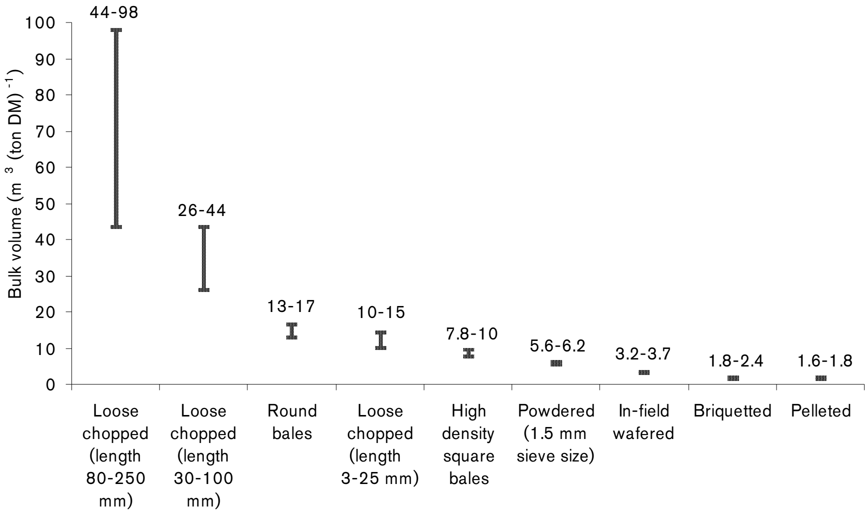


Figure 3. Bulk volume (m^3 (DM ton)$^{-1}$) of wheat straw (chopped, baled, and in-field wafered) and reed canary grass (powdered, briquetted, and pelleted). Sources: wheat straw (Nilsson, 1991), loose chopped straw, 3-25 mm (O'Dogherty & Gilbertson, 1988), powdered reed canary grass (Segerud, 1993), briquetted reed canary grass (Paulrud & Nilsson, 2001), pelleted reed canary grass (own data, Paper III).

1.4 Biofuel pelletizing

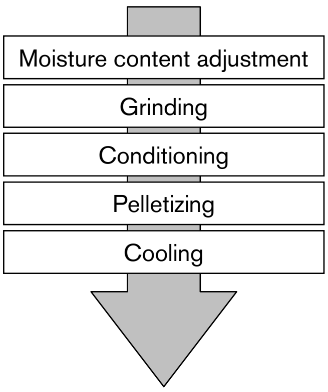


Figure 4. Process flow at a biofuel pellet plant.

Raw material arrives at biomass fuel pellet plants as chopped/chipped material, bales or logs. Thus, an initial size reduction step may be necessary to produce particles of a size suitable for moisture adjustment and/or grinding. For the vast majority of raw materials, grinding is necessary to reach a particle size distribution suitable for pelletizing. Steam conditioning adds heat and moisture to the raw materials just before pelletizing. After pelletizing, cooling is required to stabilize the pellets. (Figure 4).

1.4.1 Pellet quality

In Europe, fuel pellet quality is regulated on the basis of standards set by the European Committee for Standardization (CEN) (CEN, 2005a). Standards are normative – different quality classes are defined – and informative – specified information has to be provided to the customer (Table 2).

Table 2. *Property specifications for pellets derived from chemically untreated biomass (CEN, 2005a): specification type, and generally desired values*

Specification	Specification type	Desired value
Pellet dimensions	Normative	Low
Moisture content	Normative	Low
Ash content	Normative	Low
Mechanical durability	Normative	High
Amount of fines	Normative	Low
Amount of additives	Normative	Low
Net calorific value	Informative	High
Bulk density	Informative	High
Chlorine content	Informative	Low

Pellet dimensions

The CEN standard specifies that the maximum allowable pellet diameter is 25 mm. The diameter of traded pellets is predominantly 6 to 8 mm.

Moisture content

Moisture in pellets reduces the net calorific value. At moisture contents above 15% (wet base[4]), the risk of micro-organism growth during storage increases (e.g. Lehtikangas, 2000).

Ash content

High ash content reduces the net calorific value and constitutes a residual product that will have to be dealt with after end-use. Compared to forest based biomass, agricultural energy crops generally have higher ash contents.

Mechanical durability

Durability of pellets is an important property to minimize dust emissions during handling, transport and storage. Dust emissions can be a health hazard

[4] All moisture contents are stated in weight-%, wet base.

to people handling pellets, disturb boiler feeding systems, and increase the risk of fire and explosion during shipping, handling, and storage (Temmerman *et al.*, 2006).

Amount of fines

A high level of fines is a symptom of low durability; the amount of fines is, for the same reasons described for durability, best kept to a minimum.

Bulk density

For transport and storage, high bulk density is desirable, the higher the better. For end-use, e.g. to ensure consistent conditions for boiler feeding systems, a uniform bulk density is even more important.

1.4.2 Process technology

Vertical ring die pelletizing, considered to be the cheapest compression process in terms of both purchase price and energy consumption for animal feed pellet production (Heinemans, 1991), also is the dominant production technology for fuel pellets.

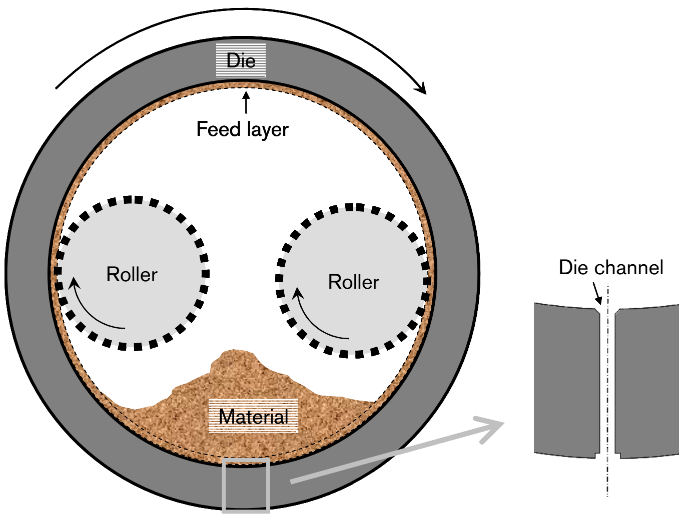


Figure 5. Schematic representation of a vertical pelletizer with rotating die and two rollers, and of one single die channel.

A ring die has a number of die channels, through which compressed raw material is forced by the mechanical pressure applied by each roller (Figure 5). Die channels are placed in rows or other geometric patterns.

Generally, material enters the feeding area above and from the side, falling freely from the end of a screw feeder. The raw material encounters the rotation of the die surface and, according to the law of inertia, enters the gap between die and rollers where friction causes the rollers to rotate. The material is compressed between the die and the rollers and a continuous feed layer is formed on the inside surface of the die. As more material is fed into the die, the die-facing side of the feed layer is forced to break up and enter the die channels. Additional parts of the feed layer are punched out and added to the columns of compressed material that are pressed through the die channels each time a roller passes. Thus, the pelletizing process is predominately governed by frictional forces for feeding the material through and much of the energy consumption in pelletizing is required to overcome friction as the pellets move through the die channels.

The main process variables influencing pellet quality are raw material moisture content and process temperatures (e.g. Arshadi *et al.*, 2008; Tabil & Sokhansanj, 1996). The influences that these variables exert on pellet quality are highly complex, since they govern multiple raw material-specific functions in the pelletizing process, including friction properties, compressibility, and relaxation (post-compression expansion).

Moisture content

Bulk density of briquettes and wafers from different straw materials is generally negatively correlated with moisture content or has a bulk density optimum at low moisture content, generally <10%. The corresponding durability optimum occurs at higher moisture contents: >10% (e.g. O'Dogherty & Wheeler, 1984; Orth & Löwe, 1977; Srivastava *et al.*, 1981).

For barley straw wafers, decreasing bulk density at higher moisture contents was due to an increasing relaxation with increasing moisture content: maximum compressed density was reached at 22% whereas maximum relaxed density was found at 6% which was the lowest moisture value of the experimental design (Faborode, 1989). However, due to relaxation, stable briquettes from oven-dry wheat straw could not be produced by Smith *et al.* (1977).

Process temperatures

Durability has been found to be positively correlated and pelletizer power consumption negatively correlated to raw material temperature for alfalfa pelletized in the temperature range 60 to 90°C (Hill & Pulkinen, 1988). Lower power consumption at higher die temperatures (from 30 to 93°C) has been reported for alfalfa and bermudagrass wafering (Hall & Hall, 1968). To reach a specific density in wheat straw briquetting, an interchangeability between die temperature (60 to 140°C) and compression load has been found, with higher temperatures giving lower relaxation rates (Smith et al., 1977). On the other hand, rye grass wafers were reported to have a bulk density optimum and a weak durability optimum at die temperatures of 40 to 50°C (Orth & Löwe, 1977).

Combinations of moisture content and temperatures

Several interaction effects between moisture content and temperature occur during the pelletizing process. Moisture content influences frictional properties of the raw material and, consequently, the frictional heat emitted at different moisture contents results in different pelletizing process equilibrium temperatures (Orth & Löwe, 1977), and high temperatures cause drying of the raw materials.

Steam conditioning prior to pelletizing is commonly known to improve the pelletizing properties of raw materials, but by adding heat and moisture at the same time, causes and effects are confounded by the complexity of the process.

Other process parameters

Durability of cereal straw briquettes reportedly decreases with decreasing average raw material particle sizes (Faborode & O'Callaghan, 1987; O'Dogherty & Wheeler, 1984). In alfalfa pelletizing, durability has been found to decrease with increasing sieve size (2.8 to 6.4 mm sieve; pellet diameter: 6.4 mm) (Hill & Pulkinen, 1988). Furthermore, particle size distribution and particle form may influence the pelletizing process and raw material-specific functions in the pelletizing process.

Generally, compressive pressure and pellet density are positively correlated until maximum density is reached. For different straw types – corn stover, and switchgrass – maximum density was found to be reached in the compressive pressure range 70 to 120 MPa (Mani *et al.*, 2006a).

In the research for Paper III, RCG pelletizing was performed with bulk density and durability as responses and moisture content, steam addition, raw material density, and die temperature, as factors.

1.4.3 Friction mechanisms

Friction between raw material particles and machinery (wall friction), and internal friction between raw material particles are highly relevant in the pelletizing process. Initially, when raw material is fed into the die, low normal stresses are applied to the raw material as frictional forces determine the feeding pattern of each raw material. In roll compaction theories, the wall friction and internal friction of raw materials, determined by shear tests according to the theories of Jenike, (1964), are positively correlated to the compression rate at the roll surface (Dec *et al.*, 2003; Johanson, 1965).

When pellets are forced through the die channels, wall friction has to be overcome. Pressure build-up inside the die channels has been estimated to reach values between 100 and 400 MPa (Köser *et al.*, 1982; Sokhansanj & Wood, 1990; Wild *et al.*, 2007).

Coefficients of internal friction and wall friction, respectively, have different values depending on whether the conditions are static or kinematic. For powders experiencing consolidation, internal static friction increases with time due to an increase in interparticle adhesive forces, i.e. the same mechanisms facilitating binding in compaction processes (Schulze, 2008). The same pattern is recognized for wall friction.

In the pelletizing process, material is fed continuously into the feed layer, but each die channel receives material intermittently, including short time intervals when no material is received. Consequently, both static and kinematic wall friction has to be overcome in the die channels.

In the work associated with Paper IV, the influences of moisture content and normal stress on the kinematic wall friction properties of RCG powder at high (65 to 376 MPa) and low (500 to 7520 Pa) stresses were determined.

1.5 Objectives

The overall objectives of the research behind this thesis were to determine supply potentials for reed canary grass (RCG), exemplified on a regional scale, and to determine the optimum process settings for the production of high quality RCG pellets. The research presented in this thesis covers: (i) remote sensing analysis in the form of an aerial photo interpretation model to estimate the costs of converting abandoned arable land to energy crop production; (ii) regional RCG supply curve analysis using a partial equilibrium approach; (iii) multiple response optimization of pellet quality parameters in an experimental design involving four different pelletizing process factors; and (iv) determination of the kinematic wall friction properties of RCG powder at high and low normal stresses.

Specific objectives were to:

- develop a remote sensing tool for the identification of abandoned farmland with low preparation costs, and which is suitable for energy crop production (Paper I).

- create RCG supply curves for three different subsidy scenarios within the EU's Common Agricultural Policy (CAP) for Västerbotten County, Sweden and identify the spatial distribution of potential supplies (Paper II).
- determine process settings for high-quality RCG pellet production by multiple response optimization, and evaluate raw material pre-compaction as a method for achieving continuous production of RCG pellets (Paper III)
- determine kinematic wall friction properties of RCG powder at high and low normal stresses (Paper IV).

2 Materials and methods

An overview of the materials, data sources, analytical methods, modelling methods, software, instruments, and equipment used in the research associated with Papers I–IV is presented in Tables 3 and 4.

Table 3. *Overview of materials, data sources, analytical methods, instruments, and equipment used in Papers I-IV. Papers I and II focus on RCG supply potential, and Papers III and IV focus on pelletizing technology*

Studies based on:	I	II	III	IV
Materials and data sources				
Black and white digital orthophotos	x			
GIS-layers relating to agricultural objects	x	x		
Digital maps of regional quaternary deposits (soil types)	x			
Delayed harvested RCG, variety Palaton			x	x
Analytical methods				
Database compilation	x	x		
Orthophoto interpretation	x			
On-site evaluation of field preparation requirements	x			
Spatial data analysis	x	x		
Sieve analysis			x	
Bulk density analysis			x	x
Pellet durability analysis			x	
Shear tests at low normal stresses				x
Shear tests at high normal stresses				x
Instruments and equipment				
Pelletizer line at SLU BTC, Umeå, Sweden			x	
Lignotester			x	
Schulze ring shear tester				x
Powder friction measuring device (PFMD)				x

Table 4. *Overview of modelling methods and software used in Papers I-IV.*

Studies based on:	I	II	III	IV
Modelling				
Univariate modelling	x	x		
Principal component analysis (PCA)	x			
Experimental design			x	x
Multiple linear regression (MLR)			x	x
Multiple response optimization			x	
Software				
ArcView 3.2	x	x		
Minitab	x	x		
SIMCA	x			
Agriwise		x		
MODDE			x	x

2.1 Supply potentials

2.1.1 Data sources

Black and white digital photos (fly height: 9200 m) were used to assess abandoned farmland (Paper I). Soil types were determined from regional maps of quaternary deposits (Anonymous, 2002a).

The actions required for the preparation of individual abandoned fields were evaluated by a local farmer, who has extensive experience of field preparation and drainage work. Required actions were assessed by visiting and walking across each individual field.

Costs for the different preparation actions were determined in collaboration with a local drainage contractor by visiting sites at which typical preparation activities would be necessary; this was followed by a mock tendering procedure.

County Administration agricultural land use databases were compiled and used for the work described in Papers I-II. Spatial information (field area and perimeter, x- and y-coordinates) and current land use (as stated by farmers in subsidy applications) were available for all agricultural land in the designated areas.

Data on eligible agricultural subsidies for different land uses were gathered from different subsidy information pamphlets published by the Swedish Board of Agriculture, and from the European Commission's proposal for a new agricultural policy (Anonymous, 2003b). Statistics on animal husbandry were obtained from Statistics Sweden (Paper II).

2.1.2 Modelling and software

Principal component analysis (PCA) was used to select a sample of fields to be visited (Paper I). From scatter plots of the first to third principal components (t1/t2; t2/t3; t1/t3), peripheral objects and some centre points were chosen to cover most of the variation associated with the seven database variables. The software used was SIMCA (Anonymous, 2002b).

The software ArcView, version 3.2 (Anonymous, 1996) was used for analyzing and handling the spatial data utilized in Papers I and II.

Analysis of variance (ANOVA), t-tests and linear regression analysis in Paper I were conducted using Minitab (Anonymous, 2003a).

Spatially selected data aggregations derived from ArcView files and production cost calculations for all viable agricultural land uses from the on-line software Agriwise (Öhlmér et al., 2002) were used as inputs for the Excel modelling of supply curves described in Paper II. The spatial distribution of agricultural land was visualised using ArcView.

2.1.3 Analytical methods

The interpretation of black and white digital orthophotos of abandoned fields described in Paper I was performed in ArcView (scale 1:5000) by manual assessment of two different indices: ditch index and field index. Indices were assigned values of 1 (no signs of woodland invasion) or 2 (woodland invasion recognizable), i.e. the combined indices were (1,1), (1,2), (2,1), and (2,2). Fields with the index combination (1,1) were classified as group A, and the remaining fields were classified as group B. The rate of interpretation was approximately 100 ha h^{-1}.

The mean preparation cost per hectare for classes A and B, and for fields with different soil types were calculated as follows:

- Grouping
- Summation of total area, A_t and total cost, C_t of all fields in each group
- Calculation of mean preparation cost $C_{\bar{x}}$ (SEK $(ha)^{-1}$) as:

$$C_{\bar{x}} = \frac{C_t}{A_t}$$

- Calculation of the root mean squared error, RMSE (under these conditions equal to the standard error (SE) of the mean estimator, SE mean), for each group as:

$$RMSE = \sqrt{\frac{\sum \left(x_i - \bar{x}\right)^2}{n(n-1)}} \qquad \text{where} \qquad x_i = \frac{(C_i - C_{\bar{x}}) \times A_i}{A_{\bar{x}}}$$

and, for each specific group, $\overline{x}$ was the mean value of x_i, n was the number of fields, C_i was the observed preparation cost (SEK (ha)$^{-1}$) of the *i*th field, $C_{\overline{x}}$ was the mean preparation cost (SEK (ha)$^{-1}$), A_i was the area of the *i*th field, and $A_{\overline{x}}$ was the mean field area.

For determination of RCG supply curves under different EU subsidy schemes (Paper II), certain conditions had to be applied:

- Agricultural land for which the County Administration had received no EU subsidy applications was designated as abandoned farmland.
- The energy crop potential was calculated on the basis of the assumption that farmers would switch to energy cropping when profitability equalled or exceeded that from the current land use.
- Farmland required for dairy production or which qualified for environmental subsidies was excluded.

2.2 Pelletizing process technology

2.2.1 Materials

Delayed harvested, round baled reed canary grass (RCG) (*Phalaris arundinacea* L.), variety Palaton, cultivated in Umeå, Sweden (63.50°N, 20.15°E) with an initial moisture content of approximately 15-20% was used as the raw material for the work described in Papers III and IV. RCG round bales were shredded in a single shaft shredder (Lindner Micromat 2000, Lindner-Recyclingtech GmbH, Spittal, Austria) with a sieve size of 15 mm. To obtain different raw material densities, pre-compaction of RCG was performed. The shredded material was dried (drying wagon with forced ventilation and a 10 kW electrical heater), briquetted (Bogma M60, Bogma AB, Ulricehamn, Sweden) and re-shredded. Different raw material densities were obtained by mixing different proportions of loose and pre-compacted RCG.

Each pelletizing experiment (Paper III) required approximately 150 kg of raw material. Material was mixed and moisture content adjusted to the desired values in a mixing wagon with a screw blender. Water was added to increase the moisture content to a desired value. After preparation, raw material was stored in sacks at approximately 15°C for a minimum of 48 h. Just before pelletizing, raw material was milled in a hammer mill with a sieve size of 4 mm. The milled material was used to determine the moisture content and density of the raw material.

Approximately 2 and 1 L, respectively, were prepared from milled (sieve size: 4 mm) RCG for wall friction analyses at high and low normal stresses (Paper IV). Samples for high normal stress analysis were moisture adjusted from their initial value of 11.4% by either adding water with a spray bottle while stirring, or by drying in a warm air oven (50°C). Samples for low normal stress analysis were a mixture of different proportions of loose and pre-compacted material, which were dried (drying wagon) to approximately 6% m.c. and then the moisture was adjusted by water addition. Mixing was performed in a 30 L bucket with a spiral mixer mounted on a power drill. Samples were sealed in plastic bags and kept for at least 48 h.

2.2.2 Experimental procedures

Pelletizing experiments and raw material preparation were performed at the research pilot plant of the Biofuel Technology Centre (BTC) at the Swedish University of Agricultural Sciences in Umeå, Sweden, using the equipment listed in Table 5.

Table 5. *Main BTC equipment used for raw material preparation and pelletizing experiments*

Equipment	Manufacturer	Capacity
Shredder, Lindner Micromat 2000	Lindner-Recyclingtech GmbH, Spittal, Austria	2000 kg h^{-1}
Briquette press, Bogma M60	Bogma AB, Ulricehamn, Sweden	500 kg h^{-1}
Pelletizer with hammer mill, SPC PP300	Sweden Power Chippers, Borås, Sweden	300 kg h^{-1}

Sieve analyses were performed with sieve sizes of 0.14, 0.25, 0.50, 0.80, 1.00, 1.40, and 2.00 mm, with a 10-minute test duration (Paper III). Bulk density analyses of raw material (50 L bucket) and pellets (6 L bucket) were conducted according to the CEN technical specification (CEN, 2005b). Pellet durability tests were conducted with a LignoTester (Lignotech, Vargön, Sweden); pellet samples were exposed to an air stream causing the pellets to collide with each other and with the perforated walls of the test chamber according to the standard procedure described by Temmerman *et al.* (2006).

Moisture content analyses, based on wet weight were conducted according to the CEN technical specification (CEN, 2004).

Pelletizing experiments were performed using an SPC PP300 Compact pelletizer (Sweden Power Chippers, Borås, Sweden). A die with a channel length of 55 mm and a die channel diameter of 8 mm was used for all experiments. A constant production rate of approximately 150 kg h^{-1} was used for each of the 19 experiments. Pelletizer current (A), die temperature (°C), temperature of raw material (°C), and steam temperature (°C) were measured continuously. Current was measured with a Satellite-U (Mitec Instrument AB, Säffle, Sweden) at 1 Hz frequency, and temperatures with a testo 177-T4 (testo AG, Lenzkirch, Germany) at 0.1 Hz frequency.

In Paper IV, kinematic wall friction was determined by shear tests and the coefficient of friction was calculated from the ratio between measured shear stress, τ, and applied normal stress, σ. A Powder Friction Measuring Device (PFMD), developed and described by Solimanjad (2003), was used for determination of the coefficient of kinematic wall friction at high normal stresses (65 to 376 MPa) and a Schulze Ring Shear Tester (Dr.-Ing. Dietmar Schulze Schüttgutmesstechnik, Wolfenbüttel, Germany) for determination of the coefficient of kinematic wall friction at low normal stresses (500 to 7520 Pa).

A method for shear tests at high stress levels was developed from the method described by Solimanjad (2003), adjusting it to allow meaningful data gathering when conducting measurements on RCG powder samples. Ring shear testing at low normal stress was performed according to a standard method (ASTM, 2008).

2.2.3 Response variables

In Paper III, the coefficient of variation of pelletizer current, cv_A, was used as a response variable to quantify uneven pellet production, where cv_A was defined as:

$$cv_A = \frac{\sigma}{\mu}$$

where σ was the standard deviation based on ampere measurements each second and μ was the mean value of pelletizer current during each measurement period. A threshold to differentiate between continuous and uneven pellet production was set at cv_A equal to 0.2. Uneven pellet production, variable pellet quality, and high wear on the machinery were experienced at cv_A values above 0.2. Runs where cv_A exceeded 0.2 were not included in the modelling of the pellet quality responses bulk density (kg m^{-3}), and durability (%).

The studied responses in Paper IV were the coefficients of kinematic wall friction at high and low normal stresses, μ_H and μ_L, calculated as:

$$\mu_H \text{ or } \mu_L = \frac{\tau}{\sigma}$$

where τ was the shear stress (Pa) and σ was the normal stress (Pa) measured in shear tests at high and low normal stresses, respectively.

2.2.4 Modelling

The work underlying papers III and IV made use of experimental design tools, to enhance the multivariate evaluation and modelling of results. RCG material was prepared at pre-set levels for moisture content (%) and raw material density (kg m^{-3}) to fit the experimental design of each experimental series (Figure 6). For Paper III, raw material was prepared according to a 2×4 level design (moisture content × raw material density) with three centre points. Two levels of steam addition (expressed in weight-% of increased moisture content), and three centre points lead to a 2×2×4 experimental design with 19 experiments in total. Each experiment involved three three-minute measurement periods (runs), during which the data was collected for modelling.

For Paper IV, raw material for tests at low normal stresses was prepared according to a 6×4 level design (moisture content × raw material density) (Figure 6). Eight levels of normal stress for wall friction measurements led to a whole design of 6×4×8 measurements. At high normal stresses, raw material density was held constant. Moisture content was set at four levels (Figure 6). Normal stress could not be controlled, and thus, normal stress was modelled as an uncontrolled factor.

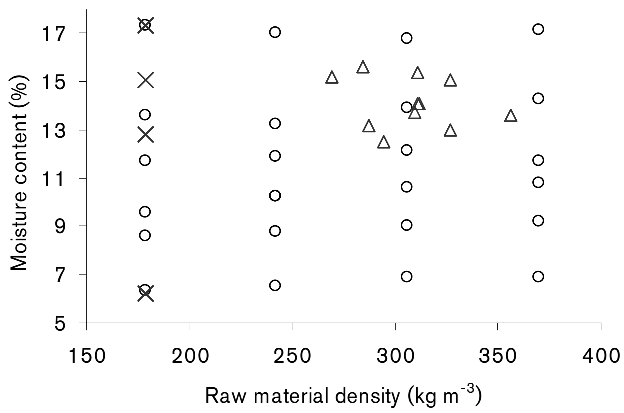


Figure 6. Distribution of moisture content (%) and raw material density (kg m^{-3}) of RCG samples in the experimental designs for Papers III and IV. △ Paper III, pelletizing experiments; ○ Paper IV, friction analysis at low normal stresses; × Paper IV, friction analysis at high normal stresses.

Multiple linear regression (MLR) was used for modelling the measured responses of controlled and uncontrolled factors. In Paper III, required factor settings to reach the desired pellet quality response value could be identified by the use of multiple response optimization. Experimental design, modelling, and multiple response optimization were performed using MODDE (Anonymous, 2006).

3 Results and discussion

3.1 Supply potentials

As a result of the partial equilibrium modelling described in Paper II, supply curves for RCG in the region of Västerbotten County, northern Sweden were constructed. The constraints applied were that farmland required for animal husbandry and farmland currently eligible for environmental subsidies were excluded; this reduced the available area from 84,000 ha to 51,000 ha. Accordingly, the proportion of available farmland, consisting of abandoned fields, increased from 23% to 37%.

Under the assumption that RCG would be produced if profitability equalled or exceeded the return from the current land use, bioenergy feedstock equalling 1.3 TWh[5] would be supplied under all EU subsidy schemes at a farmgate fuel price ≥ 116 SEK $MW^{-1}h^{-1}$ (valid for price levels in 2003). The lowest required fuel price was found under the "current" (valid until 2004) EU subsidy scheme, where production equalling 370 GWh[6] would be supplied at a farmgate price of 56 SEK $MW^{-1}h^{-1}$. The highest fuel prices were required for production on abandoned farmland with high preparation costs, whereas the required fuel price for production on abandoned farmland with low or no preparation costs was similar to costs on farmland with another ongoing use.

A remote sensing method to separate abandoned farmland with respectively low and high preparation costs was developed and evaluated (Paper I). By aerial photo interpretation, fields could be divided into two significantly ($p< 0.05$) different classes, A and B, with low (on average

[5] 1 TWh=3.6 PJ

[6] 1 GWh=3.6 TJ

173 SEK $(ha)^{-1}$) and high (on average 3990 SEK $(ha)^{-1}$) preparation costs, respectively.

From the calculations for perennial crop production costs (Rosenqvist, 1997) used in Paper II, it can be concluded that the annuity value of the mean preparation costs per hectare of fields in class A constitutes less than one percent of the total annuity costs of RCG production. Land rental costs, and alternative values of abandoned farmland are negligible, and thus, abandoned farmland of class A is of great interest for low cost production of RCG.

Decreasing preparation costs with increasing soil particle size (in the order peat, fine sediment, moraine, and coarse sediment) were found to be significant, but a significant ($p<0.05$) difference between mean preparation costs (SEK $(ha)^{-1}$) was only found between fields with fine and coarse sediments (Figure 7).

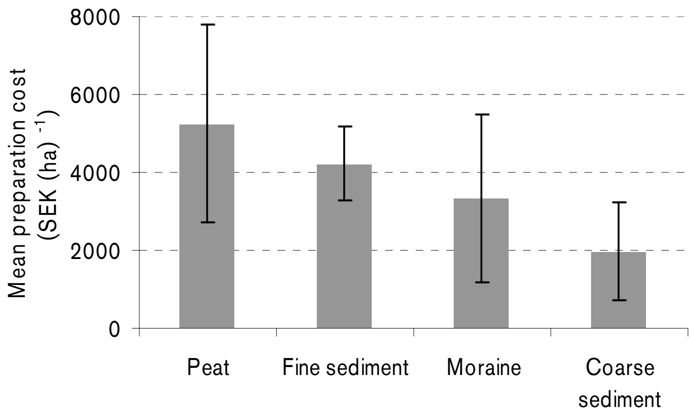


Figure 7. Mean preparation costs (SEK $(ha)^{-1}$) of abandoned fields with different soil types. Error bars indicate the 95% confidence intervals.

3.1.1 Market situation in Västerbotten County

In the winter of 2007-2008, heating companies in Västerbotten County were willing to pay approximately 150 SEK $MW^{-1}h^{-1}$ for RCG delivered to the heating plant (Nilsson, 2008). Transport and storage costs could not exceed 34 SEK $MW^{-1}h^{-1}$ if producers were to reach the required 116 SEK $MW^{-1}h^{-1}$ for profitability in RCG production. Depending on the choice of handling system, storage and transport costs vary greatly. In a study by Bernesson & Nilsson (2005) on the handling costs of straw, the total cost for seasonal storage, 200 km truck transport, and handling at the heating plant varied between 15 and 135 SEK $MW^{-1}h^{-1}$ (Figure 8).

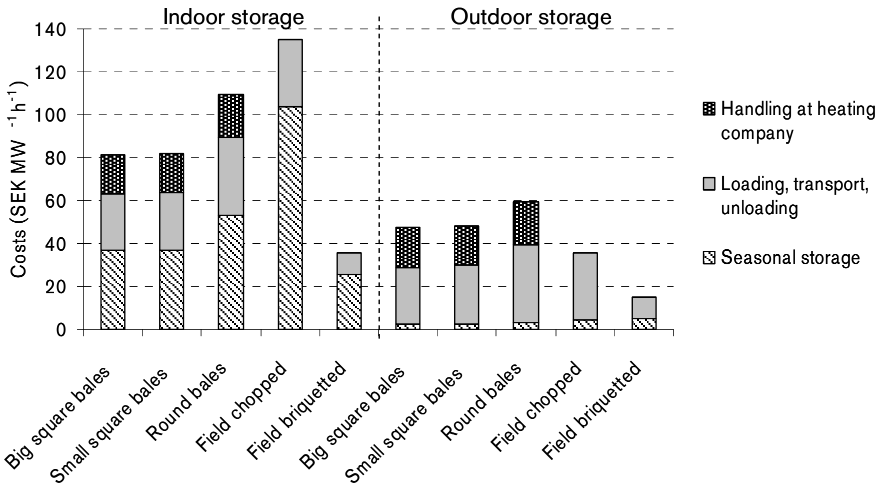


Figure 8. Handling costs (seasonal storage, loading, 200 km truck transport, unloading, and handling at the heating plant) for straw in different forms, stored inside (left) and outside (right) (Bernesson & Nilsson, 2005).

The production costs determined in Paper II were calculated for big square bales for farmgate delivery. If the chain is to follow that presented in Figure 8, outdoor storage would be the only feasible alternative at a plant gate fuel price of 150 SEK $MW^{-1}h^{-1}$. However, losses during outdoor storage can be substantial and fuel quality impaired to such an extent that indoor storage becomes a more economic solution (Bernesson & Nilsson, 2005).

In 2006, more than 17,000 ha of RCG were cultivated in Finland for delivery at the plant gate for a fuel price of 67 SEK $MW^{-1}h^{-1}$ (Pahkala *et al.*, 2008). This makes it clear that differences in agricultural subsidies have a huge influence on the profitability of RCG production.

3.1.2 Transaction costs affecting the implementation potential

In a study by Paulrud & Laitila (2007) on Swedish farmers' attitudes to energy crop cultivation, the most frequently stated reason for not cultivating energy crops was low profitability. In areas where only RCG and hemp were feasible (northern Sweden), the main reasons given for not cultivating an energy crop were low profitability (50%) and practical problems at cultivation/harvest (31%). When evaluating different qualities of RCG, the long crop rotation time (10 years) was considered to be the most undesirable, whereas the use of existing machinery for cultivation and harvest and the possibility of delivery contracts between farmer and buyer were seen as positive features.

The reasons that farmers in Ostrobothnia, Finland, cultivated RCG were: less work (compared to traditional agriculture) (38%), the need for a change from a current unprofitable production sector (35%), and subsidies (28%) (Pahkala *et al.*, 2008).

Compared to other farmland uses, abandoned farmland is generally considered to be of low aesthetic value (e.g. Benjamin et al., 2007; Tahvananinen et al., 1996). Land owners are resistant to tree plantations on farmland for traditional and cultural reasons (Neumann et al., 2007). Thus, the added value of retaining an open landscape is probably important when choosing whether to produce RCG on abandoned farmland.

3.1.3 Practical use of planning tools

In Enköping, mid-Sweden, the local energy company is considering the possibility of leasing farmland to increase Salix production (McCormick & Kåberger, 2005). For the land owner, leasing out farmland reduces the risk and minimizes work but may return little profit. In areas of declining agriculture with part-time farmers, and when land owners live elsewhere, farmland leasing could be an efficient way of increasing energy crop production. Compared to waiting for a land owner initiative, preparation and cultivation of abandoned farmland through a system of leasing is more likely to be implemented.

The planning tools described in Papers I and II would be beneficial for targeting areas of suitable farmland when energy crop production is organized on a larger scale, for example, via public land leasing. A spatial overview of farmland and the possibility of targeting abandoned farmland with low preparation costs are useful tools in the decision making process, allowing planners to focus on appropriate areas.

3.2 Pelletizing process technology

3.2.1 Uneven pellet production

Before setting up the factorial design described in Paper III, extreme conditions where sought, under which steady state pellet production could be sustained long enough for meaningful data gathering (Figure 9). The lowest feasible raw material bulk density, found at the lowest moisture content, with no steam addition, was 260 kg m^{-3}; this is approximately 60% higher than the natural density of milled RCG.

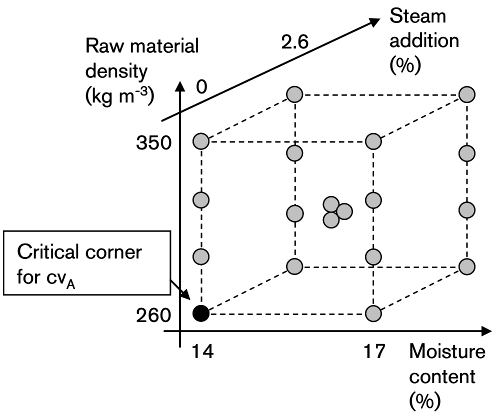


Figure 9. Factorial design for the pelletizing experiments described in Paper III.

Within the range of the design, moisture content (%) was the most influential factor and was negatively correlated to the coefficient of variability of the pelletizer current, cv_A. In addition, cv_A was found to be positively correlated to die temperature. In practice, when pelletizing low density RCG, this is manifested by initial smooth production when the die is relatively cold, but as die temperature increases, production becomes uneven, and finally ceases (Figure 10).

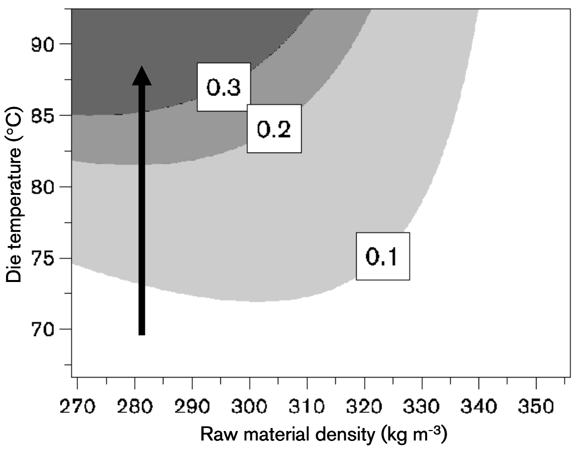


Figure 10. Response surface of the coefficient of variability of pelletizer current, cv_A, as a function of raw material density (kg m^{-3}) and die temperature (°C) at 12.5% moisture content and 1.3% steam addition. The arrow shows a typical die temperature increase during RCG pelletizing.

3.2.2 Pellet quality

Within the range of the design (Paper III), raw material moisture content was the most influential factor for the pellet quality responses: pellet bulk density (kg m^{-3}) and pellet durability (%). RCG pellets showed a negative correlation between moisture content and pellet bulk density and a moisture content optimum for pellet durability. This is in line with previous studies on a range of straw materials. However, to reach a high pellet quality, defined in Paper III as a bulk density ≥ 650 kg m^{-3} and a durability ≥ 97.5%, there was a discrepancy between moisture content optima for the two quality responses, and the production window where both pellet quality responses were fulfilled was very narrow (Figure 11).

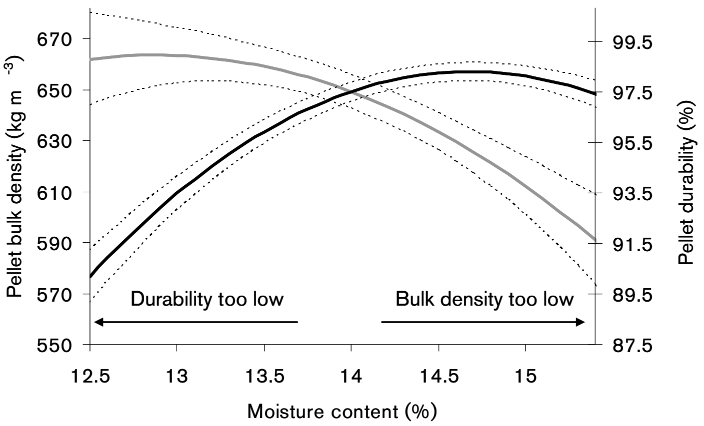


Figure 11. Modelled pellet bulk density (kg m^{-3}) (grey line) and durability (%) (black line) at different raw material moisture contents. Other factors were held constant at their design centre values; steam addition: 1.3**%;** raw material density: 312.5 kg m^{-3}; die temperature: 79.5 °C. Black dotted lines indicate the 95% confidence intervals of the responses.

3.2.3 Process settings

By multiple response optimization, the required settings for all modelled factors to obtain high quality pellets, with a bulk density ≥ 650 kg m^{-3} and a durability ≥ 97.5%, could be found. These settings can be visualized in a four-dimensional chart (Figure 12) where black areas indicate the settings where both constraints are fulfilled.

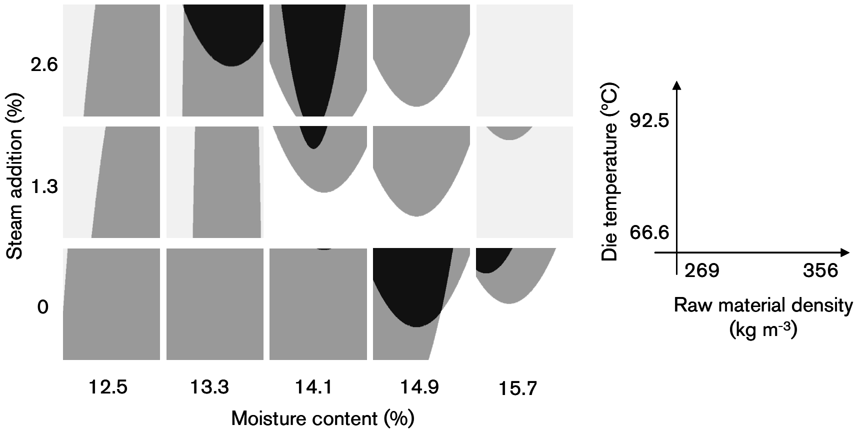


Figure 12. Multiple response surface for the pellet quality parameters bulk density ≥ 650 kg m^{-3} and durability $\geq 97.5\%$. Light grey: no constraint met, medium grey: one constraint met, black: both constraints met. The major x-axis shows five different levels of moisture content (%) and the major y-axis shows three different levels of steam addition (%). The minor x- and y-axes (to the right) show continuous values for each square in the multiple response surface, x-axis: raw material density (kg m^{-3}) and y-axis: die temperature (°C).

The use of a multiple response surfaces to visualize settings for high quality pellets is an example of how to communicate the results of research to process operators at pelletizing plants. Charts could be created for different raw materials and representing relevant factors.

3.2.4 Kinematic wall friction properties

The coefficient of kinematic wall friction followed a for many bulk products general pattern in the normal stress interval of 0.5 to 7.5 kPa, being positively related to moisture content and negatively correlated to normal stress. Decreasing wall friction with decreasing moisture content could, in part, explain why the feed layer is lost when pelletizing RCG at increasing die temperatures (Figure 10): a high die temperature may cause drying of the feed layer. In addition, die temperature could be negatively correlated to wall friction. However, in a comparison between pine stemwood powder and RCG powder at room temperature and at moisture contents common for pelletizing, coefficients of kinematic wall friction for RCG powder do not appear to be significantly lower (Figure 13), and pine stemwood powder has no tendency to cause uneven pellet production.

To reach continuous pelletizing conditions in the experiments described in Paper III, RCG had to be pre-compacted. However, raw material density was not found to be significant for modelling the coefficient of kinematic wall friction at low normal stresses, and hence, the beneficial qualities of a density increase were not due to increased kinematic wall friction.

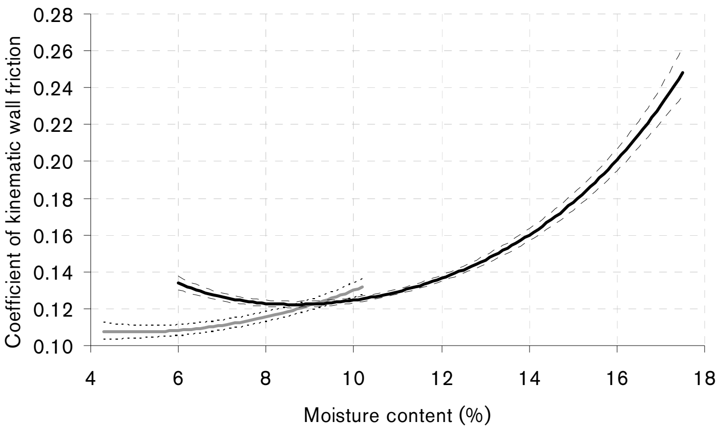


Figure 13. Modelled coefficients of kinematic wall friction for pine sawdust powder (grey line) and reed canary grass powder (black line) at 4 kPa normal stress and at different raw material moisture contents (%). Dotted black lines indicate the 95% confidence intervals. Pine sawdust model from own unpublished data (R^2=0.82).

A rapid increase in kinematic wall friction with increasing normal stress was found in the normal stress interval 50 to 150 MPa. This increase was most pronounced for samples with moisture contents of 12.8 to 15.1%. Also, samples with 6.3% moisture content showed a positive correlation with normal stress, although the gradient was less steep (Figure 2 in Paper IV).

MLR modelling of observations of the coefficient of kinematic wall friction within the normal stress interval of 65 to 376 Pa, showed a maximum at moisture contents of 13-16%, and normal stresses of 150-225 MPa (Figure 3 in Paper IV). A similar behaviour, indicating a friction maximum at intermediate moisture contents, was reported for alfalfa extrusion (Hann & Harrison, 1976).

During measurements it was observed that when the friction coefficient exceeded values of approximately 0.18, a glassy layer appeared on the sample shear surfaces. From experience, a smooth glassy surface is characteristic of RCG pellets with a high durability. Hence, a relationship between durability and kinematic wall friction was suggested. The moisture content optimum for RCG pellet durability was found within the interval 14 to 15.5% (Paper III), coinciding with the kinematic wall friction coefficient maximum described in Paper IV.

Unpublished data on the coefficient of kinematic wall friction at high normal stresses for Scots pine powder showed the same pattern of increase in the 150–225 MPa normal stress interval. Further studies will be needed to determine kinematic wall friction properties for different biomass fuel pellet raw materials and to understand how these properties influence the pelletizing process, especially in the normal stress interval where the shift in kinematic wall friction was observed.

The kinematic wall friction measurements described in Paper IV were performed at room temperature (approximately 25°C), whereas the die temperatures used in the work underlying Paper III varied within the range 67 to 93°C. Wall friction of pine stemwood powder has been shown to be significantly lower at 125°C than at 60°C at compression pressures of 300 to 400 MPa (Nielsen et al., 2008). This implies that, in a continuously operated pelletizing process, an initial low die temperature with high kinematic wall friction creates frictional heat that increases the die temperature and at increased die temperatures, kinematic wall friction decreases until a local steady state is reached.

Orth & Löwe (1977) conducted a study on continuous wafering of ryegrass at stress levels from approximately 10 to 100 MPa, where the mean maximum piston force was measured at uncontrolled and controlled die temperatures and at different initial moisture contents. From data in this article, a model with an explained variation of 89% was created to predict the mean maximum piston force from the factors: initial raw material moisture content (%), die temperature (°C), and the squared factor of moisture content. The contour plot in Figure 14 shows the modelled mean maximum piston force at different die temperatures and different initial moisture contents, when die temperature was controlled. White dots indicate conditions after 20 minutes of wafering at different initial moisture contents when die temperature was uncontrolled. In practice, production conditions for each initial moisture content move from left to right (and may also drift towards lower actual moisture content due to drying of the material) until reaching a local steady state position in the die temperature versus moisture content plot. In the contour plot in Figure 14, a maximum for the modelled mean maximum piston force is found within the initial moisture content interval of 15 to 17% and at low die temperatures.

If the mean maximum piston force has a linear relationship with static and kinematic wall friction, coefficients of wall friction for ryegrass powder will decrease with increasing die temperatures, reaching a maximum within the moisture content interval of 15 to 17%.

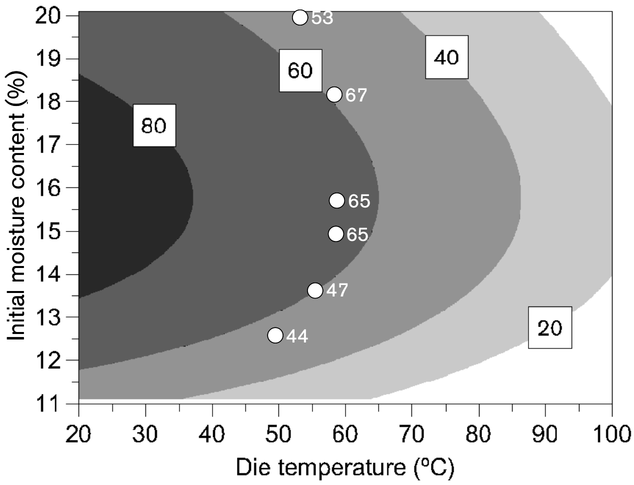


Figure 14. Response surface of the mean maximum piston force (kN) during continuous wafering of ryegrass from experiments with different controlled die temperatures (°C) and different raw material moisture contents (%). White dots labelled with mean maximum piston force (kN) values indicate conditions from corresponding experiments with uncontrolled die temperatures after 20 minutes of wafering. Data from Orth & Löwe (1977).

Steady state die temperatures at different moisture contents are governed by, for example, compaction equipment dimensions, ambient temperature, and various process settings. For each individual setup, a different steady state die temperature arises, out of the control of the operator, and, thus, die temperature will influence pellet quality and energy consumption in uncontrolled ways. Hence, die temperature control would be valuable for enhancing the opportunities for optimizing continuous compaction processes.

From results in Paper III and from the literature reviewed, the conclusion must be that future research on biomass fuel pelletizing requires experimental setups where more variables are controlled in the experimental situation, in order to elucidate fully the interrelated effects of moisture, temperature, friction, compressibility, etc., on pellet quality parameters and process efficiency. The discovery of a kinematic wall friction peak at high normal stresses, intersecting with moisture content intervals for maxima in the coefficient of kinematic wall friction (Paper IV) and pellet durability (Paper III), may open up new possibilities for improving pelletizing techniques. Results imply that, with existing pelletizing techniques, a high kinematic wall friction within die channels is required to create a durable RCG pellet surface. To overcome friction, more mechanical energy is used than is needed to reach the necessary bulk density of the pellets (c.f. Mani et al., 2006b). Consequently, development of alternative pelletizing technologies, involving less energy consumption to attain high durability, should be encouraged and may be very successful.

4 Conclusions

Abandoned farmland with low preparation costs, suitable for energy crop production, can be identified and distinguished from abandoned farmland with high preparation costs using black and white digital orthophotos and digital farmland databases in a GIS environment.

Supply curves for RCG on a regional level, taking other land uses into consideration, and under different subsidy scheme scenarios within the EU's Common Agricultural Policy were created and exemplified for Västerbotten County, northern Sweden. The main area of high potential for energy crop production was located in the coastal part of Västerbotten County.

Pre-compaction of RCG powder to a certain minimum density is one method for achieving continuous pelletizing conditions.

Required settings of importance for process operators for the production of high quality RCG pellets were identified by multiple response optimization. A discrepancy between moisture content optima for pellet bulk density and durability results in narrow production windows for high quality RCG pellets.

At low normal stresses (0.5 to 7.5 kPa), the coefficient of kinematic wall friction for RCG powder decreases with increasing normal stress and is positively correlated with moisture content.

At normal stresses of 50 to 150 MPa, a steep increase in the coefficient of kinematic wall friction for RCG powder was found. The moisture content intervals to achieve maxima in the coefficient of kinematic wall friction for RCG powder and in RCG pellet durability coincided. It was hypothesized that the two properties are correlated. Discovering a local maximum in the kinematic wall friction at high normal stresses suggests that less energy-consuming pelletizing technology could be developed by searching for alternative ways of achieving high pellet durability.

5 Future research

In order to increase the proportion of renewable energy available, exemplified, for example, by the EU's 20% target for 2020 (Anonymous, 2008), the results from studies of biomass supply chains are important for providing politicians with reliable data on how to stimulate increased production of biomass for energy use. Throughout the EU, market situations, production conditions, etc., are very variable, with specific interactions between crop, environment, management, and the market. Hence, in order to be effective, initiatives have to be well adapted to local conditions.

In the future, close co-operation between researchers, biomass producers, industrial partners, consumers, and politicians, to develop a series of long-term energy supply systems of manageable sizes, will probably have the best potential for success and for being applicable to local and regional situations. By creating such arenas for research and development, the interests of all parties could be better addressed and the pace of development and implementation would probably increase.

The rapid growth of the international wood pellet market provides evidence of the potential for the increased use of biomass for energy purposes through the development of economically beneficial technologies. The worldwide feedstock supply of forestry and agricultural residues and dedicated energy crops constitutes a huge resource that, through research into the optimization of compaction processes, could be introduced into the world's energy systems. Optimization of processes for the densification of all biomass raw materials is the ultimate target in research to be implemented on an industrial scale and, in this case, is of immediate relevance for the increased use of biomass as an energy source.

However, basic research to determine and isolate the causes and effects of different process parameters on quality responses and process efficiency is needed to facilitate any significant improvement in densification processes. In Paper IV, controlled experiments on RCG powder resulted in a hypothesis about the relationship between raw material moisture content, normal stress, kinematic wall friction, and pellet durability. For a better understanding of the friction mechanisms governing the pelletizing process, and other compaction processes, more laboratory-scale studies on the frictional behaviour of biomass powders where normal stress, moisture content, temperature, etc., can be varied in a controlled environment, should be performed. For the determination of wall friction and internal friction at high normal stresses, measuring devices and analytical methods need to be further developed.

Better control of the die temperature could lead to a substantial increase in the number of feasible process settings by introducing a new parameter for process control and removing an uncontrolled factor that causes uncontrolled effects. Additionally, variability between process conditions in different pelletizers could be reduced and recipes for the process settings for different raw materials could be more widely applicable.

Furthermore, pilot scale development of alternative biomass powder compaction technologies for the reduction of energy consumption, whilst maintaining or improving product quality, has great potential and is of greatest interest.

A multidisciplinary approach to the research and development of technologies for biomass compaction for energy purposes has great potential and could be designed as follows:

- Basic research in controlled environments to increase knowledge about the relationships between the physical and chemical properties of biomass feedstock, process parameters, process mechanisms and quality responses.
- Pilot scale studies on compaction technologies, in which basic research studies are applied in a mechanical engineering environment
- Calibration of chemical and physical analyses, pilot and industrial scale process parameters, and product quality responses using different spectroscopic analysis methods, e.g. near infrared spectroscopy (see Lestander & Rhen, 2005), in order to build up databases. This would be followed by implementation with process monitoring on-line or at line.

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