A Viable Strategy to Sugar Cane Lignocellulosic Bio-Ethanol Development in Southern Africa

Sabatha Thulane Qwabe

Dissertation submitted to the Faculty of Science for the Doctor of Philosophy Degree

School of Environmental Sciences and Environmental Studies
University of KwaZulu-Natal, Durban

Sabic Productions
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Funded by Sabic Group (Pty) Ltd
Material Production by Sabic Productions

Dedicated to my late grandfather, Elijah Hlophe

https://www.fleet.ford.com/products/alternative vehicles/flexible fuel/2004-mountain-comparison.asp


2005 Chevy Silverado & GMC Sierra Flexible Fuel Ethanol (E85) Pickups

http://www.gm.com/automotive/innovations/altfuel/

Abstract

In the current era, oil deficit countries around the world seriously consider shifting dependence from conventional gasoline to renewable bio-ethanol fuel in the transport industry. Arguably, blending 10vol% dry ethanol with 90vol% unleaded gasoline enables ethanol fuel to penetrate the fuel market at relatively lower development costs. Despite creating an important market for the ethanol industry, fuels containing dry ethanol of differential proportions multiply the local risks associated with fuel combustion. Making a sale of one drop of ethanol fuel, for example, is intrinsically tied to the sale of more drops of imported gasoline. Furthermore, an increase (decrease) in conventional fuel prices directly influences a decline (increase) in daily sales of ethanol fuel. Blending bio-ethanol fuel with conventional gasoline in various proportions fails to address the multifaceted fossil fuel crisis in oil deficit countries. Although reducing bio-ethanol production costs can buffer fuel prices to a significant degree when blended in higher ratios, industrial competition for bio-feedstock is a serious limitation for bio-ethanol development in all parts of the globe. Nevertheless, advances in biotechnology may allow the use of a wide range of cheaper ethanol feedstocks (e.g. lignocellulose) leading to an important reduction in ethanol production costs.

Temporal and spatial variability of lignocellulosic ethanol potentials in the sugar industry is investigated over southern Africa as a whole. The influence of extremely low (high) production of sugar cane on the potentials development of lignocellulosic ethanol plants is demonstrated in this work. Characterization of bio-ethanol fuel markets on the basis of blending with gasoline is undertaken at the subcontinental scale. The connectivity between development, consumption per capita, population growth, bio-ethanol energy demand, as well as the critical limits of land stock potentials is examined in this study. On the basis of the special influence that each of the processes indicated above have on bio-ethanol fuel development, an integrated approach toward optimizing the total value of bio-ethanol fuel in the region is formulated. This approach allows the investigation to determine whether critical and beyond critical conditions of land stock lead to a collapse of a human consumption type or whether bio-ethanol fuel development is a totally viable process. Finally, this work ascertains whether sustainable biofuel development is an oxymoron

because human development demands a constantly growing fuel consumption per capita, or because of increasing the lower limit, with an infinite upper limit for human development, or as a product of the combined effects of increasing human population with a higher consumption rate per capita of non-growing and non-developing land stock units.

Declaration

The work presented in this dissertation was carried out from 2003 to 2004 under the supervision of Professor Gerry Garland and Dr. Helen Watson. I declare that the work is my original innovation and has never been submitted previously for any degree at any other university. The use of non-original material has been fully acknowledged in the report. Findings presented are reflective of the information used at the time of investigation. I hold no guarantees whatsoever about the accuracy of the information for any particular use, or otherwise, in affected or related sections of industrial development. This work is in no way can be regarded as a feasibility analysis of bio-ethanol fuel in southern Africa. Furthermore, the study is not intended to compare cane lignocellulose with other food crops, but as a possible feedstock that can be used to counter the limitations of food crops where their availability is dependent on inefficiencies of the food markets. Conclusions made therefore relate to cane lignocellulose as a dedicated feedstock for ethanol fuel production. Rights for use of any original material given in this work toward industrial development other than pure information developmental research are reserved. The study was funded by Sabic Group (Pty) Ltd. Material production was undertaken by Sabic Productions (Pty) Ltd

Name: Sabatha Thulane Qwabe

Signed: ……………………………………

Date: May, 2004

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List of Abbreviations

BBI	BBI International Co.
BCI	BCI International, Inc.
BDT	Bone dry ton
BP	British Petroleum (Ltd)
E10	10% ethanol blend with petrol
E85	85% ethanol blend with petrol
ETOH	Ethanol
GIS	Geographic Information System
K	in thousand (,000)
KTY	Thousand tons per year
MGY	Million gallons per year
MLY	Million litres per year
MT	Metric Ton (1000kg)
MMT	Methylcylopentadienyl Manganese Tricarbonyl
MTBE	Methyl Tertiary Butyl Ether
SACU	Southern African Customs Union
SADC	Southern African Development Community
SASA	South African Sugar Association
SASEX	South African Sugar Experiment Station
SKPE	Swaziland Komati Programme Enterprise
SSCF	Simultaneous saccharification and co-fermentation
SSF	Simultaneous saccharification fermentation
U.S.A.	United States of America (U.S.)
U.S.DOE	U.S. Department of Energy
U.S.NREL	U.S. National Renewable Energy Laboratory

Units

Units and conversion factors

1 Metric Tonne (Ton) = 1000 kilograms (kg)

1 US Barrel (bbl) = 42 gallons = 159.0 litres (gal)

1 US Gallon (gal) = 3.785 litres (l)

1 bushel = 56 Pounds

1 Pound (lb) = 0.454 kilograms (kg)

1kilogram = 2.205 pounds

1 hectare (ha) = 2.47 acres

789kg ethanol = 1000 litres of ethanol

Energy and Biofuel Conversion Factors

Ethanol

Energy content (LHV) = 75700 Btu/gallon = 80 MJ/gallon = 21 MJ/liter
Energy content (HHV) = 84000 Btu/gallon = 89 MJ/gallon = 23 MJ/liter
Density (average) = 0.79 g/ml
1 GJ ethanol = 12.5 gallons (LHV)

Gasoline

Energy content (LHV) = 115000 Btu/gallon = 121 MJ/gallon = 32 MJ/liter
Energy content (HHV) = 125000 Btu/gallon = 132 MJ/gallon = 35 MJ/liter
Density (average) = 0.73 g/ml
1 GJ gasoline = 8.2 gallons (LHV)

Energy values are commonly provided in two types of units, HHV (gross) or LHV (net) and both sets of values are given for reference. LHV figures are used in this report. HHV = Higher Heating Value (also gross heat content) which is all energy released during combustion. LHV = Lower Heating Value (also net heat content) where the energy used to vaporize water contained or released during combustion is subtracted. LHV is derived assuming 6.5% Hydrogen content.

Source: http://bioenergy.ornl.gov/papers/misc/energy_conv.html;
http://www.ott.doe.gov/biofuels/properties_database.html

Glossary

Additives: Chemicals added to fuel in very small quantities to improve and maintain fuel quality. Detergents and corrosion inhibitors are examples of gasoline additives.

Air Toxics: Those pollutants that cause or may cause cancer or other serious side effects.

Alcohols: Organic compounds that are distinguished from hydrocarbons by the inclusion of a hydroxyl group. The two simplest alcohols are methanol and ethanol.

Aldehydes: A class of organic compounds derived by removing the hydrogen atoms from an alcohol. Aldehydes can be produced from the oxidation of an alcohol.

Alternative Fuel: Methanol, denatured ethanol and other alcohols; mixtures containing 85% or more by volume of methanol, denatured ethanol and other alcohols with gasoline or other fuels; natural gas; liquefied petroleum gas; hydrogen; coal-derived liquid fuels; non-alcohol fuels (such as biodiesel) derived from biological material; and electricity. ^{3}P-Series^2 fuels were added to this list since the original definition in the EPAct. Alternative Fuel Vehicle (AFV) As defined by the Energy Policy Act, any dedicated, flexible-fuel or dual-fuel vehicle designed to operate on at least one alternative fuel.

American Society for Testing and Materials (ASTM): A non-profit organization that provides a management system to develop published technical information. ASTM standards, test methods, specifications and procedures are recognized as definitive guidelines for motor fuel quality as well as a broad range of other products and procedures. Anhydrous describes a compound that does not contain any water. Ethanol produced for fuel use is often referred to as anhydrous ethanol, as it has had almost all water removed.

Antiknock Index (AKI): measures the ability of gasoline to resist engine knock/ping. AKI is the average of the Research and Motor Octane (or (R+M)/2). Commonly referred to as the pump octane.

Aromatics: Hydrocarbons based on the ringed six-carbon benzene series or related organic groups. Benzene, toluene and xylene are the principal aromatics, commonly referred to as the BTX group. They represent one of the heaviest fractions in gasoline.

BTX: Industry term referring to the group of aromatic hydrocarbons benzene, toluene and xylene (see Aromatics).

Balance of Payments: The dollar amount difference between a country^{1}s exports and imports. In the United States, large oil imports are one of the main causes of the negative balance of payments with the rest of the world. In Swaziland this is the same issue.

Biochemical Conversion: The use of enzymes and catalysts to change biological substances chemically to produce energy products. For example, the digestion of organic wastes or sewage by microorganisms to produce methane is a biochemical process.

Biodiesel: A biodegradable transportation fuel used in diesel engines that is produced through transesterification (see definition in this glossary) of organically derived oils or fats. Biodiesel is used as a component of diesel fuel, but is not condoned for use in any GM vehicle.

Biomass: Renewable organic matter such as agricultural crops, crop-waste residues, wood, animal and municipal waste, aquatic plants, fungal growth, etc., used for the production of energy. British Thermal Unit (BTU) A standard unit for measuring heat energy. One BTU represents the amount of heat required to raise one pound of water one degree Fahrenheit (at sea level).

Butane: A gas, easily liquefied, recovered from natural gas. Used as a low-volatility component of motor gasoline, processed further for a high-octane gasoline component, used in LPG for domestic and industrial applications and used as a raw material for petrochemical synthesis.

Butyl Alcohol: Alcohol derived from butane that is used in organic synthesis and as a solvent.

Carbon Dioxide (CO2): A product of combustion that has become an environmental concern in recent years. CO2 does not directly impair human health but is a ^{3}greenhouse gas^2 that traps the earth^{1}s heat and contributes to the potential for global warming. Carbon Monoxide (CO) A colorless, odorless gas produced by the incomplete combustion of fuels with a limited oxygen supply, as in automobile engines.

Carbon Sequestration: The absorption and storage of CO2 from the atmosphere by the roots and leaves of plants; the carbon builds up as organic matter in the soil.

Catalyst: A substance whose presence changes the rate of chemical reaction without itself undergoing permanent change in its composition. Catalysts may be accelerators or retarders. Most inorganic catalysts are powdered metals and metal oxides, chiefly used in the petroleum, vehicle and heavy chemical industries.

Cetane: Ignition performance rating of diesel fuel. Diesel equivalent to gasoline octane.

Clean Diesel: An evolving definition of diesel fuel with lower emission specifications, which strictly limit sulfur content to 0.05% weight; in California, aromatics content is further limited to 10% volume (for large refiners).

Clean Fuel: Any fuel or power source that is used to certify a vehicle to the LEV, ILEV, ULEV, SULEV or ZEV standard.

Closed-Loop Carburetion: System in which the fuel/air ratio in the engine is carefully controlled to optimize emissions performance. A closed-loop system uses a fuel metering correction signal to optimize fuel metering.

Compression Ignition: The form of ignition that initiates combustion in a diesel engine. The rapid compression of air within the cylinders generates the heat required to ignite the fuel as it is injected.

Converted or Conversion Vehicle: A vehicle originally designed to operate on gasoline or diesel that has been modified or altered to run on an alternative fuel.

Cryogenic Storage: Extreme low-temperature storage.

Dedicated Vehicle: A vehicle that operates solely on one fuel.

Denatured Alcohol: Ethanol that contains a small amount of a toxic substance, such as methanol or gasoline, which cannot be removed easily by chemical or physical means. Alcohols intended for industrial use must be denatured to avoid federal alcoholic beverage tax.

Detergent: Additives used to inhibit deposit formation in the fuel and intake systems in automobiles.

Distillation Curve: The percentages of gasoline that evaporate at various temperatures. The distillation curve is an important indicator for fuel standards such as volatility (vaporization).

Domestic Fuel: Domestic fuel is derived from resources within Swaziland (which may include South Africa in certain cases).

Driveability index: is a specification used to manage engine performance during cold weather and whilst the engine is warming up. Driveability problems usually show as hesitation and stumbling when accelerating, uneven idling and surging when cruising.

Dual-Fuel Vehicle: Vehicle designed to operate on a combination of an alternative fuel and a conventional fuel. This includes vehicles using a mixture of gasoline or diesel and an alternative fuel in one fuel tank, commonly called flexible-fuel vehicles, and vehicles capable of operating on either an alternative fuel, a conventional fuel or both.

E10 (Gasohol): Ethanol mixture containing 90% gasoline and 10% ethanol, by volume.

E85: Ethanol/gasoline mixture containing 85% denatured ethanol and 15% gasoline, by volume.

E93: Ethanol mixture containing 93% ethanol, 5% methanol and 2% kerosene, by volume.

E95: Ethanol/gasoline mixture containing 95% denatured ethanol and 5% gasoline, by volume.

Electricity: Electric current used as a power source. Electricity can be generated from a variety of feedstocks including oil, coal, nuclear, hydro, natural gas, wind and solar. In electric vehicles, onboard rechargeable batteries power an electric motor.

Emission Standards: Limits or ranges established for pollution levels emitted by vehicles as well as stationary sources. The first standards were established under the 1963 Clean Air Act. Emissions limits are imposed on four classes of vehicles: auto-mobiles, light-duty trucks, heavy-duty gasoline trucks and heavy-duty diesel trucks.

Ester: An organic compound formed by reacting an acid with an alcohol, always resulting in the elimination of water.

Ethanol (also known as Ethyl Alcohol, Grain Alcohol, CH3CH2OH): Can be produced chemically from ethylene or biologically from the fermentation of various sugars from carbohydrates found in agricultural crops and cellulosic residues from crops or wood. Used in the United States as a gasoline octane enhancer and oxygenate, it increases octane 2.5 to 3.0 numbers at 10% concentration. Ethanol also can be used in higher concentration in alternative-fuel vehicles optimized for its use.

Ether: A class of organic compounds containing an oxygen atom linked to two organic groups.

Etherification: Oxygenation of an olefin by methanol or ethanol. For example, MTBE is formed from the chemical reaction of isobutylene and methanol.

Ethyl Alcohol: see Ethanol.

Ethyl Ester: A fatty ester formed when organically derived oils are combined with ethanol in the presence of a catalyst. After water washing, vacuum drying and filtration, the resulting ethyl ester has characteristics similar to petroleum-based diesel motor fuels.

Ethyl Tertiary Butyl Ether (ETBE): A fuel oxygenate used as a gasoline additive to increase octane and reduce engine knock.

Ethylene dibromide and ethylene dichloride: are scavengers which function by providing halogen atoms that react with the lead in burnt engine gasoline to form volatile lead halide salts that can escape through the car exhaust pipe. The amount of scavengers added to the alkyl lead concentrate is calculated according to the amount of lead used in the fuel.

Evaporative Emissions: Hydrocarbon vapors that escape from a fuel storage tank or a vehicle fuel tank or system.

Flexible-Fuel Vehicle: Vehicles with a common fuel tank designed to run on varying blends of unleaded gasoline with either ethanol or methanol.

Flexible Volatility Index (FVI): is a parameter used to ensure good hot weather operability of the fuel by limiting the fuel volatility so that vapour lock cannot occur.

Fuel Cell: An electrochemical engine with no moving parts that converts the chemical energy of a fuel, such as hydrogen, and an oxidant, such as oxygen, directly to electricity. The principal components of a fuel cell are catalytically activated electrodes for the fuel (anode) and the oxidant (cathode) and an electrolyte to conduct ions between the two electrodes.

Gasohol: refers to gasoline containing 10vol% ethanol. IN the U.S. the term was used in the late 1970s and early 1980s, has since be replaced by terms like Super Unleaded Plus Ethanol or Unleaded Plus.

Gasoline Gallon Equivalent (gge): A unit for measuring alternative fuels so they can be compared with gasoline on an energy equivalent basis. This is required because the different fuels have different energy densities.

Global Warming: The theoretical escalation of global temperatures caused by the increase of greenhouse gas emissions in the lower atmosphere.

Greenhouse Effect: A warming of the earth and its atmosphere as a result of the thermal trapping of incoming solar radiation by CO2, water vapor, methane, nitrous oxide, chlorofluorocarbons and other gases, both natural and man-made.

Lead concentration: Leaded fuel = 1.1 g Pb / litre maximum and Unleaded = 0.0013g Pb / litre maximum.

Liter (L): A metric measurement used to calculate the volume displacement of an engine. One liter is equal to 1,000 cubic centimeters or 61 cubic inches.

Lubricity: Capacity to reduce friction.

LUSIP: Lower Usuthu Smallholder Irrigation Project.

M100: 100% (neat) methanol.

M85: 85% methanol and 15% unleaded gasoline by volume, used as a motor fuel in FFVs. GM does not condone the use of M85 in our vehicles.

Methane (CH4): The simplest of the hydrocarbons and the principal constituent of natural gas. Pure methane has a heating value of 1,012 BTU per standard cubic foot.

Methanol (also known as Methyl Alcohol, Wood Alcohol, CH3OH): A liquid fuel formed by catalytically combining CO with hydrogen in a 1-to-2 ratio under high temperature and pressure. Commercially, it is typically manufactured by steam reforming natural gas. Also formed in the destructive distillation of wood.

Methyl Alcohol: See Methanol.

Methyl Ester: A fatty ester formed when organically derived oils are combined with methanol in the presence of a catalyst. Methyl ester has characteristics similar to petroleum-based diesel motor fuels.

Methyl Tertiary Butyl Ether (MTBE): A fuel oxygenate used as an additive to gasoline to increase octane and reduce engine knock.

Mobile Source Emissions: Emissions resulting from the operations of any type of motor vehicle.

Motor Octane: The octane as tested in a single-cylinder octane test engine at more severe operating conditions. Motor Octane Number (MON) affects high-speed and part-throttle knock and performance under load, passing, climbing and other operating conditions. Motor octane is represented by the designation M in the (R+M)/2 equation, and is the lower of the two numbers.

Near Neat Fuel: Fuel that is virtually free from admixture or dilution.

Neat Alcohol Fuel: Straight or 100% alcohol (not blended with gasoline), usually in the form of either ethanol or methanol. Neat Fuel Fuel that is free from admixture or dilution with other fuels.

OEM: Original Equipment Manufacturer. The original manufacturer of a vehicle or engine.

MGY: Million gallons per year

MLY: Million litres per year

Octane Enhancer: Any substance such as MTBE, ETBE, toluene and xylene that is added to gasoline to increase octane and reduce engine knock.

Octane Number Requirement (ONR): The octane level required to provide knock-free operation in a given engine.

Octane Rating (Octane Number): A measure of a fuel's resistance to self ignition, hence a measure as well of the anti-knock properties of the fuel.

Olefins: A gasoline component resulting from several refining processes – ethylene, butylenes. Often contributes to the formation of gum and deposits in engines.

Open-Loop Fuel Control: System in which the air/fuel mixture is preset by design with no feedback correction signal to optimize fuel metering.

Oxides of Nitrogen (NOx): Regulated air pollutants, primarily NO and NO2 but including other substances in minute concentrations. Under the high pressure and temperature conditions in an engine, nitrogen and oxygen atoms in the air react to form various NOx. Like hydrocarbons, NOx are precursors to the formation of smog. They also contribute to the formation of acid rain.

Oxygenate: A term used in the petroleum industry to denote fuel additives containing hydrogen, carbon and oxygen in their molecular structure. Includes ethers such as MTBE and ETBE and alcohols such as ethanol and methanol.

Oxygenated Fuels: Fuels blended with an additive, usually methyl tertiary butyl ether (MTBE) or ethanol to increase oxygen content, allowing more thorough combustion for reduced carbon monoxide emissions.

Oxygenated Gasoline: Gasoline containing an oxygenate such as ethanol or MTBE. The increased oxygen content promotes more complete combustion, thereby reducing tailpipe emissions of CO. Ozone Tropospheric ozone (smog) is formed when volatile organic compounds (VOCs), oxygen and NOx react in the presence of sunlight (not to be confused with stratospheric ozone, which is found in the upper atmosphere and protects the earth from the sunŒs ultraviolet rays).

PGBI and AGZIM: PGBI Engineers and Constructors (Pty) Limited in association with AGZIM (PVT) Limited of Harare.

P-Series Fuels: Fuels designed by the Pure Fuel Corporation to run in E85/gasoline flexible fuel vehicles.

Paraffins: Group of saturated aliphatic hydrocarbons, including methane, ethane, propane and butane, and noted by the suffix ^{3}-ane.^{2}

Particulate Matter (PM): A generic term for a broad class of chemically and physically diverse substances that exist as discrete particles (liquid droplets or solids) over a wide range of sizes.

Particulate Trap: Diesel vehicle emission control device that traps and incinerates diesel particulate emissions after they are exhausted from the engine but before they are expelled into the atmosphere.

Petroleum Fuel: Gasoline and diesel fuel.

Phase Separation: The phenomenon of a separation of a liquid or vapor into two or more physically distinct and mechanically separable portions or layers.

Public Fueling Station: A fueling station that is accessible to the general public.

Pump Octane: The octane as posted on retail gasoline dispensers as (R+M)/2; same as Antiknock Index.

Refueling Emissions: VOC vapors that escape from the vehicle fuel tank during refueling. Storage II pump controls and onboard refueling vapor recovery systems (ORVR) are intended to control these emissions.

Reid Vapor Pressure (RVP): A standard measurement of a liquid's vapor pressure in psi at 100 degrees Fahrenheit. It is an indication of the propensity of the liquid to evaporate.

Research Octane Number (RON): The octane as tested in a single-cylinder octane test engine operated under less severe operating conditions. RON affects low to medium-speed knock and engine run-on. Research Octane is presented by the designation R in the (R+M)/2 equation, and is the higher of the two numbers.

Retrofit: To change a vehicle or engine after its original purchase, usually by adding equipment such as conversion systems.

SKPE: Swaziland Komati Programme Enterprise Ltd.

Smog: A visible haze caused primarily by particulate matter and ozone. Ozone is formed by the reaction of hydrocarbons and NOx in the atmosphere.

Spark Ignition Engine: Internal combustion engine in which the charge is ignited electrically (e.g., with a spark plug).

Stoichiometric Mass: the mass or volume of air required to provide sufficient oxygen to achieve complete combustion of engine fuel.

Sulfur Dioxide (SO2): A criteria pollutant.

Tailpipe Emissions: Vehicle exhaust emissions released through the vehicle tailpipe. Tailpipe emissions do not include evaporative and refueling emissions, which are also regulated by the EPA. The EPA publishes allowable emission levels and vehicle certification standards in the Code of Federal Regulations.

Tax Incentives: In general, a means of employing the tax code to stimulate investment in or development of a socially desirable economic objective without direct expenditure from the budget of a given unit of government. Such incentives can take the form of tax exemptions or credits.

Tertiary Amyl Methyl Ether (TAME): An ether based on reactive C5 olefins and methanol.

Tetraethyl Lead or Lead: An octane enhancer. The EPA has phased down the use of lead in gasoline as it has been determined to be a health hazard. Lead has been prohibited in highway vehicle gasoline since January 1, 1996.

Theory: refers to the amount of scavengers added in leaded gasoline react with all the lead produced during the combustion process to form the halide salts, typically 1.0 to 1.5 theories are used.

Therm: A unit of heating value equivalent to 100,000 British Thermal Units (BTUs).

Toluene: Basic aromatic compound derived from petroleum and used to increase octane. The most common hydrocarbon purchased for use in increasing octane.

Toxic Emission: Any pollutant emitted from a source that can negatively affect human health or the environment.

Toxic Substance: A generic term referring to a harmful substance or group of substances. Typically, these substances are especially harmful to health, such as those considered under the EPA's hazardous substance program. Technically, any compound that has the potential to produce adverse health effects is considered a toxic substance.

Trans-esterification: A process in which organically derived oils or fats are combined with alcohol (ethanol or methanol) in the presence of a catalyst to form esters (ethyl or methyl ester).

U.S. Environmental Protection Agency (EPA): A government agency, established in 1970, responsible for protecting the environment and public health. The EPA seeks to reduce air, water and land pollution and pollution from solid waste, radiation, pesticides and toxic substances. The EPA also controls emissions from motor vehicles, fuels and fuel

Vapor Pressure or Volatility: The tendency of a liquid to pass into the vapor state at a given temperature. With automotive fuels, volatility is determined by measuring RVP.

Variable Fuel Vehicle (VFV): A vehicle that has the capacity to burn any combination of gasoline and an alternative fuel. Also known as a flexible fuel vehicle.

Vehicle Conversion: Retrofitting a vehicle engine to run on an alternative fuel.

Volatile Organic Compound (VOC): Reactive gas released during combustion or evaporation of fuel and regulated by the EPA. VOCs react with NOx in the presence of sunlight and from ozone.

Volatility: refers to a fuel's ability to change from gas to vapour, characterized by three measurements: vapour pressure, flexible volatility index and distillation curve (commonly measure by RVP).

Voluntary Mobile Source Emission Reduction Program: A program established by the EPA to encourage voluntary emission reduction programs that can be part of a state implementation program.

Xylene: An aromatic hydrocarbon derived from petroleum and used to increase octane. Highly valued as a petrochemical feedstock. Xylene is highly photochemically reactive and, as a constituent of tailpipe emissions, is a contributor to smog formation.

Zero Emission Vehicle (ZEV): A vehicle that emits no tailpipe exhaust emissions.

In my world and your world;
Success is a divine creativity of capability;
Confined within the limits of human ingenuity;
A treasure we all share so differentially,
But falling in cyclical patterns of human adaptation;
There is no peak in natural human ingenuity,
Hence there is no peak to natural human success;
Our intelligence is a demand of the cyclical changes
Defining human consumption limitations in a confined earth;
We are all a treasure to the world for separate goals;
A gift we can all embrace with no end;
Scoring a winning goal is a bigger challenge;
Only our determination can take us all beyond just winning in face of tribulations;
Score your winning goal and I will take you beyond the winning star;
Together we shall breathe in wiser and unselfish world.

Chapter One

Introduction

1.0 Motivation

Developing bio-ethanol fuel has drawn significant global attention over the last few years. The idea has somehow brought relief to the agricultural industry, producing large amounts of renewable sources of bio-ethanol fuel on annual basis. Given that up to 85vol% bio-ethanol fuel can be blended with gasoline to run flexible motor technologies, greater attention on this biofuel is expected in the next few years. This will certainly allow bio-ethanol fuel to become a common fuel in car engines around the globe. Using higher blends of bio-ethanol fuel with gasoline can improve the efficiency of feedstock production and development. A greater reduction in prices of bio-ethanol fuel blends can be achieved, making the industry extremely competitive with other fuel sources in a free market. Also included is a significant increase in product market size with more flexible car technologies introduced into the transport market. The process will need dependable gasoline supplies and prices.

Developing bio-ethanol fuel creates numerous local benefits. Besides improving efficiencies of the local energy systems, it also integrates diverse developmental sectors into a common mainstream for economic growth and development in very important ways. These may include:

(a) creation of dependable long-term skilled and unskilled jobs in feedstock production, development, management and processing,

(b) improving local balance of payment,

(c) enhancing local energy security,

(d) complementing the changing human lifestyles defining the passage to the 3rd millennium,

(e) reducing the transfer of fossil fuel problems from the oil rich sections of the world through trade to the crude oil deficit countries,

(f) creating dependable local markets for small- to large-scale farmers, while efficiently enabling farm output diversification,

(g) providing an enabling environment for the creation of diverse industries at local level based on an eco-efficient use of crop resources, such as developing high-value co-products, and finally

(h) creating diverse local investment opportunities from feedstock production, processing, through to product marketing.

1.1 The Eco-Efficiency of Bio-Ethanol Fuel

There is no single renewable source of bio-ethanol fuel. It can be produced nearly anywhere in the world in quantities that are dependent on feedstock potentials, feedstock costs and consumption rates per capita. This observation highlights the efficiency of using renewable biomass materials for bio-ethanol fuel production. Not only that bio-ethanol fuel development provides economic and industrial benefits, it also limits the amount of gasoline used to run car engines. Bio-ethanol fuel therefore reduces dependence of local economic transformation on foreign energy, with externally regulated accessibility.

Regional demand for bio-ethanol fuel is reflected by the demand for gasoline. However, market accessibility and demand rates are dependent on various processes other than the growing scarcity of gasoline worldwide. These include (see next two chapters): (a) sources of raw materials and production costs, (b) nature of bio-ethanol as a transport fuel, (c) price acceptability and reliability, as well as the (d) fuel demand rate per capita. Understanding that bio-ethanol as a fuel has not matured yet, inefficiencies of the above-given parameters extremely limit the development of bio-ethanol fuel based solely on business principles. Hence local government incentives and subsidies are crucial for its initial success.

Bio-ethanol fuel can be blended with gasoline or used in its pure form. The most common bio-ethanol fuel blends are E10 (i.e. 10vol% ethanol fuel in 90vol% gasoline), E22 (i.e. 22-24vol% bio-ethanol fuel in gasoline), and E85 (i.e. 85vol% bio-ethanol fuel in 15vol% gasoline) (details given in Chapter Two). Among these fuel blends, E10 is widely used in the U.S.A., while E22 is the Brazilian national standard fuel. All major car manufacturers in the world accept the use of the E10 fuel blend in petrol engines without affecting the car manufacturer's warranty. Fuel blends higher than E10 are not accepted by automakers for use in petrol engines, because these blends are less compatible with the ordinary petrol engines. As a result, engine modifications are necessary when fuel blends higher than E10 are used to run cars.

The U.S.A. E85 is a special bio-ethanol fuel blend. It consists of up to 85vol% bio-ethanol fuel in gasoline. Only dedicated motor technologies run on this fuel blend, more often called the flexible fuel vehicles (FFV). More important about these FFV is that they can also run on 100% gasoline.

Whereas any organic material can be converted to ethanol, the choice of feedstock is largely dictated by the fuel economics (see Chapter Three). Although corn is widely used in some parts of the world to produce bio-ethanol fuel, cane sugar still remains the most common source of the world's bio-ethanol fuel. Other very important sources of sugar for bio-ethanol fuel production are sweet sorghum and sugar beet. The cost of bio-ethanol fuel feedstock accounts for at least 50% of the fuel production cost per unit of volume. Reducing feedstock costs is of significant importance in achieving major declines in bio-ethanol fuel consumer prices. Low cost sources such as sweet sorghum and lignocellulose (crop fibre and wood) are being developed as dedicated feedstock for bio-ethanol fuel production. The potential to produce and develop low cost lignocellulose feedstock for bio-ethanol fuel development over southern Africa is characterized in this investigation. Land stock limitations for intensive feedstock development and bio-ethanol fuel production are examined. A brief analysis of the fuel economics and market characteristics is given in this work. Attempts are made to understand whether sustainable development can be achieved in the bio-ethanol fuel industry where human population not only grows in size, but also characterized by increased fuel energy consumption rate per capita.

1.2. The Choice of Cane Lignocellulose for Investigation

Increased availability, suitability, renewability, as well as the general organization of the sugar cane industry influenced the choice of cane lignocellulose as the bio-ethanol feedstock for investigation in this study. More important is that the sugar industry provides greater information necessary to understand the implications of intensifying agricultural crop production for bio-ethanol fuel in southern Africa as a whole. Except for few processes, the development of cheaper feedstock suitable for the southern African region, such as sweet sorghum, is similar to sugar cane. Identifying the potential impacts of developing dedicated feedstocks on land stock potentials is surely a requisite for successful bio-ethanol production over the subcontinent. Further qualifying the choice of lignocellulose for this study is its low production cost in southern Africa, and around the world as well. The advantages of using lignocellulose over other agricultural sources of bio-ethanol fuel in the long-term are clear, as further highlighted in the next chapter.

Although this investigation does not extend further than identifying the production and development potentials of biomass ethanol fuel over the subcontinent (i.e. no detailed analysis of the economics and market characteristic), a general outlook of the core processes influencing the success of the industry are given in Chapter Seven. Further studies pertaining these components of biofuel development will be necessary in future. In addition, these studies need to be developed on the bases of using cheaper conversion technologies, which are proven in a commercial environment. There is still no conclusive information stating that lignocellulosic bio-ethanol fuel can be developed in a commercial environment, except the ongoing commercial tests undertaken in the U.S.A. Nonetheless, identifying the potential to produce bio-ethanol fuel from low cost renewable materials is a prerequisite for further investigations in southern Africa.

1.3. Hypotheses

The aim of the study is to investigate the viability and develop a more efficient strategy for producing bio-ethanol fuel from sugar cane lignocellulose in southern Africa. The hypotheses to be tested are that:

1. successful development of bio-ethanol as a transport fuel in southern Africa is dependent on efficient feedstock production and fuel marketing systems,
2. the variability of bio-ethanol potentials over the subcontinent as a whole closely follows the spatial and temporal distribution of cane lignocellulose,
3. under efficient production, positive (negative) departures of bio-ethanol potentials from the statistical norms can have positive (negative) influence on the economics of fuel ethanol,

4. increased bio-ethanol fuel consumption (or development) per capita rather than natural population growth creates critical limits of natural stocks, leading to beyond critical conditions of stock consumption,
5. intensive consumption of finite stock per consumption type is characterized by a single critical point, but with a series of transitional limits (stages) to form one complete consumption cycle: each stage in the cycle is defined by a unique cost for successful human adaptation,
6. human consumption over the long-term is defined by a series of complete consumption cycles (human adaptation cycles) where the adaptation costs increase for every new cycle, and finally
7. developing bio-ethanol fuel on the basis of agricultural intensification cannot be sustainable given the infinite upper limit for human development per capita.

1.4. Methodology Highlight

Defining southern Africa for the study has carefully considered the following requisites:

(a) the bio-ethanol industry interests for Swaziland and South Africa,
(b) the existing structures, market policies and regulations of the sugar cane industry that can influence the development of bio-ethanol as a fuel within the Southern African Development Community (SADC),
(c) the current trading network, which can be most efficiently used in promoting bio-ethanol fuel trade within SADC, and
(d) the accessibility to reliable cane data for the 1991-2002 period.

Delineating a manageable study area within SADC followed the preceding requisites. An important number of countries within SADC do not produce sugar cane in scales large enough for consideration in this study. With the observation that some of the sugar cane producing countries within the SADC region fail to meet the requisites for consideration in this study, the choice of the Southern African Customs Union (SACU) became the most appropriate approach for defining the southern African region here. SACU consists of five member countries, which are Botswana, Lesotho, Namibia, Swaziland and South Africa.

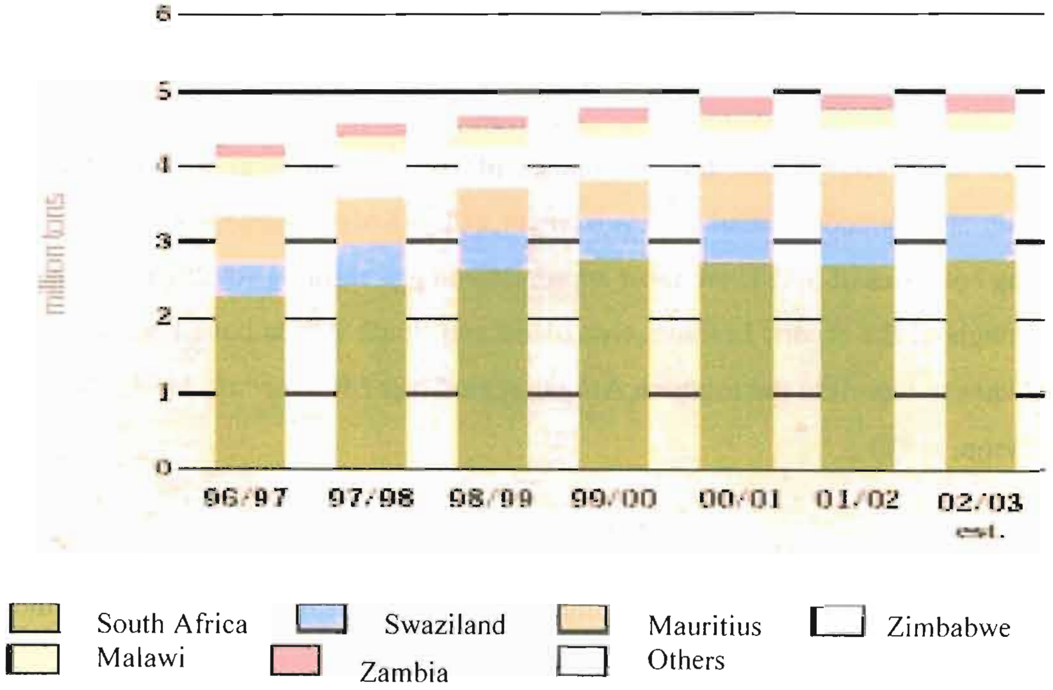


Figure 1.1: Cane sugar production in the last five years in the SADC region.

Source: http://www.illovo.co.za/worldofsugar/

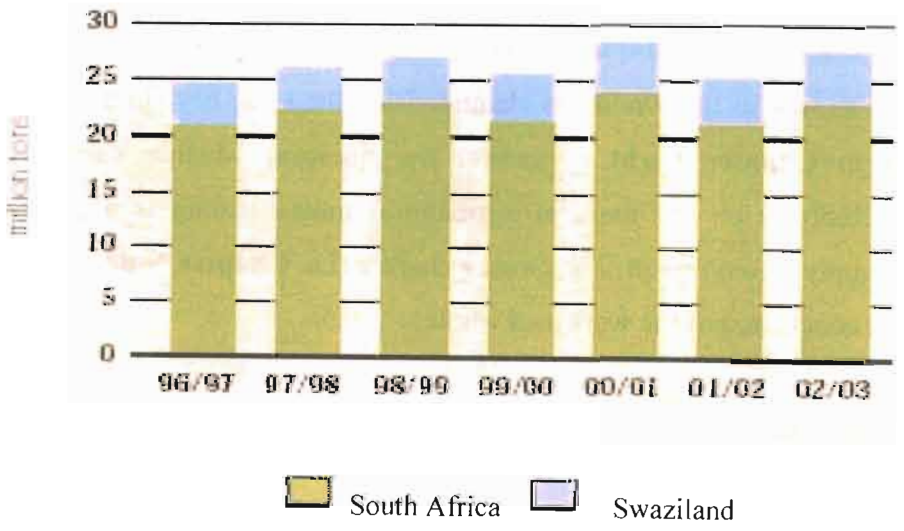


Figure 1.2: Annual sugar cane totals produced by the Southern African Customs Union countries in 1996/07 – 2002/03.

Source: http://www.illovo.co.za/worldofsugar/

Over the last five years, SACU has accounted for more than half of the total cane sugar produced in the SADC region as a whole (http://www.illovo.co.za/worldof sugar/) (Fig.1.1). Within SACU, Swaziland and South Africa are the only countries producing sugar cane in scales suitable for consideration and accountable for at least 50% of sugar cane in the SADC region (Fig.1.2).

Having acknowledged the advantages of the SACU group for bio-ethanol production and immediate market development in the SADC region, the sugar cane producing countries of SACU are most appropriate in representing southern Africa, as used throughout the report. Lesotho, Swaziland and South Africa have been used in other studies to represent the southern African region (see Mason *et al.*, 1994; Qwabe, 1999; Tyson, 1986)

The report consists of nine chapters. **Chapter One** introduces the concept of bio-ethanol fuel production using agricultural crops. The background material of the bio-ethanol industry is presented in **Chapter Two**, while **Chapter Three** examines the suitability of different agricultural crops for commercial use in producing bio-ethanol fuel. Not only that **Chapter Four** shows the approach used to test the hypotheses defining this study, it also explains the tools used to achieve the overall purpose of the work. Having presented the findings of this investigation at the regional scale in **Chapters Five** and **Six**, evaluation of these findings at the sub-regional scale is undertaken in **Chapter Seven.** Processes leading to the existence of land stock limits, as well as the conditions characterising the stage beyond the critical point are used in **Chapter Eight** to answer the question whether sustainable development of biofuels on the basis of agricultural intensification is a possible undertaking or simply an oxymoron. The closing chapter (i.e. **Chapter Nine)** presents the summary and conclusion of the work as a whole.

Having introduced the concept of the work, the next chapter offers the background materials for this study.

Chapter Two

Background

2.0 Introduction

The discussion presented in the preceding chapter briefly highlighted the purpose of bio-ethanol fuel development in southern Africa. Processes that have motivated this investigation have also been highlighted in Chapter One. This chapter presents the background of bio-ethanol as a fuel for the transport industry, which influenced the nature of this study as a whole. The process is achieved by first showing the characteristics of bio-ethanol fuel. The efficiency of fuel bio-ethanol both as an additive and an extender (blend) of gasoline is evaluated in this chapter. Characterization of the bio-ethanol-gasoline fuel blends is undertaken in this chapter. The presentation further includes an assessment of global perceptions about the energy efficiency of bio-ethanol fuel blends.

2.1 Alcohols

Alcohols are oxygenates (http://www.fao.org/docrep/T4470E/t4470e08.htm). They are named using the basic hydrocarbon that derives them. Examples of alcohols are methanol (CH_3OH), ethanol (C_2H_5OH), Propanol (C_3H_7OH) and Butanol (C_4H_9OH). Theoretically, organic molecules belonging to the family of alcohols can be used as fuel ((http://www.fao.org/docrep/T4470E/t4470e08.htm).

Fermenting monosaccharides such as glucose and fructose produces ethanol. Generally, ethanol can be manufactured by fermenting a wide variety of biomass materials. The biomass source for ethanol fuel production varies depending on local economics and resources. More often the economics dictate processes of ethanol production for use as fuel in the transport industry. This notion is important for improving the rationality of ethanol production using feedstock sources derived from agriculture. It can also enhance regional development of fuel production facilities by optimizing the efficiency of resources used in the production of ethanol. The two largest producers of ethanol, Brazil and the United States, use biomass sources that are high in carbohydrate content (see Chapter Three). Lignocellulose is another possible agricultural source of ethanol fuel.

Regardless of the biomass source, the basic process of ethanol production or recovery is the same. The process consists of three important steps, and in some cases with surrounding processes in order to optimize the overall efficiency of the production process. The three main steps that are always present are (a) hydrolysis, (b) fermentation, and (c) distillation. There are cases where the first two steps, hydrolysis and fermentation, can be undertaken simultaneously. Both ethanol production systems give a solid residue considered as a byproduct and an aqueous stream.

The importance of using ethanol either blended with gasoline (diesel) or as a stand-alone fuel for dedicated motor technologies is well understood. Below is a detailed analysis of ethanol fuel characteristics.

2.2 Characterization of Fuel Ethanol

2.2.1. Ethanol characteristics

Ethanol is miscible with water in all proportions and also with most organic solvents. It has a simple molecular structure that contains carbon, hydrogen and oxygen, with defined physical and chemical properties (Table 2.1) (Prakash, 1998; Sinor and Bailey, 1993). The oxygen in ethanol provides a cleaner and more efficient burn of the fuel. When used in vehicles, ethanol reduces carbon dioxide released to the atmosphere, which would have been released by burning nonrenewable fossil fuels (Table 2.1). Although ethanol fuel use releases carbon dioxide during production and combustion, the gas is recycled by crops that produce ethanol during the process of photosynthesis. This creates a cycle in which greenhouse gases are used instead of being emitted into the environment. The combustion of gasoline releases carbon dioxide, which is accumulated in the atmosphere. This accumulation in atmospheric carbon dioxide has been found to be partly responsible for the observed anomalous oscillations of global climates.

Table 2.1: Illustrating some of gasoline and ethanol properties.

Item	Ethanol	Gasoline
1. Formula	C_2H_5OH	C4 to C12 compounds
2. Molecular weight	46.07	100-105
3. Composition (weight %)		
(a) Carbon	52.17	85-88
(b) Hydrogen	13.1	12-15
c. Oxygen	34.7	0.0
4. Boiling point @ 1 atm. °C	78.3-78.5	27-225
In °F	172-173	80-437
5. Density (kg/l)	0.792 (6.61 lb/gal)	0.72-0.78 (6.0-6.5 lb/gal)
6. RVP (kPa)	15-17	50-100
7. Blending (kPa)	118-144	50-100
8. Heat of vaporization (KJ/kg) (or Btu/lb)	842-930 (362-400)	330-400 (140-170)
9. Lower Heat Value (KJ/kg)/ (KJ/l) (or Btu/lb)	27,000 / 21,200 / 11,600	43,000 / 31,800 / 18,500
10. Autoignition Temp. (oC)	365-425	257
11.Flamability limits (vol%)	3.3-19.0	1.0-830
12. Stoichiometric A/F (Kg/Kg)	8.9-9.0	14.7
13. Equivalent Volume (LHV) (l/l of gasoline)	1.53	1.0
14. RON	102-130	90-100
15. MON	95-106	80-92
16. (R-M)/2	96-113	85-95
17. Blending RON	112-120	90-100
18. Blending (MON)	95-106	80-92
19. Viscosity (centipoises @ 20oC	1.19	0.37-0.44
20. Water solubility (Vol% @ 21oC)	100	negligible
21. Carbon dioxide (Kg/Kg) fuel	1.91	3.18

Source: http://www.ec.gc.ca/transport/publications/ethgas/ethgas4.htm;

http://www.goodrichsugar.com/ethanol.asp.

2.2.2 Fuel ethanol

Although ethanol has been traditionally considered as a beverage product for use in spirits, beer and wine, ethanol is an excellent alternative to leaded gasoline fuel (http://www.comalc.com/fuel_ethanol.htm). Ethanol is used as an automotive fuel. There are suggestions that most of the cars currently available can run on fuel ethanol blends (http://www.comalc.com/fuel_ethanol.htm; http://www.ethanol-gec.org/clean/cf14.htm).

In the U.S.A., the use of ethanol to run cars dates as far back as 1908. Henry Ford developed his Model T to run on ether gasoline or pure alcohol (North West Regional Biomass Program, 2001). Ethanol, as a transport fuel, is used either as an additive (i.e. 10vol% anhydrous ethanol is blended with 90vol% gasoline), gasoline fuel extender (i.e. blending more than 10vol% ethanol with gasoline) or in its pure form.

From 1975 to 1998, total energy consumption in Brazil increased from nearly 4500 PJ to 9900 PJ (BEN, 1999). According to Moreira (2000), during the same period gasoline consumption dropped from 520 PJ (12% of the energy market) to 490 PJ (5%), a clear indication of the success of the alcohol program, which started in 1975. Moreira further stated that factors leading to the oil substitution program included (a) an increase in ethanol production, which accounted for 19.7% of the total fuel consumed by the transportation sector and 3.5% of total energy consumed, and (b) sales of more than 700,000 automobiles powered by neat ethanol (95% of total sales) in 1989, the peak year of ethanol participation. Since 1989, continuous reduction in the number of neat ethanol cars produced led to sales in 1998 of less than one thousand units (Moreira, 2000; Moreira and Goldemberg, 1999). Despite these circumstances, consumption of ethanol fuel continued to increase up to 1998 due to the existing fleet of neat ethanol cars and the increase in the number of cars, which used a blend of 22vol% ethanol in gasoline. In 1998, ethanol represented 3.4% of the total energy consumed in the country. Macedo (2000) claimed that the sugar cane agro-industry in Brazil is a very important example of a sustainable biomass to energy large-scale system. Macedo made this assertion on the basis that the energy output/input ratio (renewable/fossil fuel) is about 9.2, leading to an extraordinary value of carbon dioxide abatement (i.e. nearly 20% of all fossil fuel emissions in Brazil).

2.2.3. Ethanol-gasoline fuel blends

Motor vehicles manufactured from the 1970s can run on E10 (http://www.e10unleaded.com/whosays.htm). The E10 blend does not need car engine modification and therefore recommended by all car manufacturers. According to Prakash (1998), up to 10vol% ethanol in gasoline (gasohol) have been blended with conventional gasoline to run cars designed to burn gasoline in Canada and the U.S.A. for more than two decades. Although the initial use of fuel ethanol was driven by the need for energy security and fuel diversity, the octane quality and environmental benefits became the important drivers of ethanol fuel development in these countries, Prakash further highlighted.

Blending gasoline with lower volumes of fuel ethanol has serious negative implications for the ethanol industry. While ethanol blends with gasoline of up to 10vol% are important in penetrating the transport industry, it largely limits efficient growth of the market size, thus leading to:

(a) lower volumes of ethanol produced per unit of time,
(b) non-competitive marketing strategies of ethanol as a transport fuel,
(c) inefficient growth and development of ethanol markets, as they remain tied to volumes of gasoline sales,
(d) higher prices of fuel ethanol than gasoline, where the latter benefits from the economy of scale,
(e) greater reduction of returns on investments,
(f) creating two parallel forms of local dependence on the petroleum industry (i.e. in addition to gasoline supplies for blending, ethanol producing countries have to depend on gasoline to make ethanol sales – no gasoline sale means no ethanol fuel sale), and
(g) greater subsidies and incentives for ethanol development as a transport fuel, a process that undermines capital investment in ethanol fuel production, particularly in the developing world.

2.3. Limitations of Bio-Ethanol Fuel Blends

Using higher ethanol volume percentages in gasoline improves the total viability of ethanol development. However, increasing the concentration of fuel ethanol in gasoline has additional cost-attachments, such as increased capital investments. These extra cost-attachments more often impair investment on ethanol fuel production in developing countries like Swaziland, with a small fuel market size. Strategic rationalization of ethanol development as a fuel is a requirement for successful integration of ethanol with the transport industry in non-competitive fuel markets.

Higher ethanol/gasoline blends are used in Brazil and the U.S.A. as well. Bolling and Suarez (2001) suggested the blending ratio of 20-24vol% (commonly known as E22 fuel) and 76-80vol% with gasoline in Brazil. The Alcohol Interministerial Committee comprising of representatives of the Ministry of Agriculture, Finance, Mines and Energy, as well as Industrial Development and Commerce determines the composition of ethanol in gasoline, stated Bolling and Suarez. The cross trends between hydrous and anhydrous ethanol uses in Brazil complicate ethanol demand and market development. After the oil crisis of the early 1970s, blending higher volumes of ethanol with gasoline was responsible for the peak of anhydrous ethanol demand in 1989, when cheaper gasoline became available (Moreira, 2000; Moreira and Goldemberg, 1999). The oil price increase experienced in 2001 improved ethanol sales, pushing a greater proportion of the fuel blends more to 22vol% than 20vol% ethanol in gasoline (Bolling and Suarez, 2001).

In the U.S.A., the use of higher ethanol volumes of gasoline has received greater attention in more recent years (http://iogen.ca/3200.html; http://www.e85fuel.com/new/073004fyi.htm). Unlike in Brazil, the U.S.A. is currently promoting the use of fuel blends containing as high as 95vol% ethanol in gasoline (http://www.ethanol.org). Running dedicated motor technologies with a fuel blend of 85vol% ethanol in gasoline (E85) is becoming more attractive in the U.S.A (Fabi, 2004). This fuel blend significantly reduces the demand of foreign gasoline. Benefits of using this fuel blend can be easily realized in the U.S.A. in the event of another major global oil crisis. Although running cars on E85 can improve financial savings from importing foreign fuels, extreme oil shortages can have serious implications for the ethanol industry where the 15vol% gasoline used is foreign. For example, during extremely low supplies of gasoline, two fuel conditions would develop. Firstly, ethanol can neither efficiently buffer the high price of gasoline in the selling price of the local fuel nor can it be used to run cars when gasoline supplies fail to meet the required volume for producing E85 fuel. Secondly, sales of fuel ethanol would fail to balance the production costs, irrespective of the higher demand for ethanol fuel blends. Hence the process would force a reduction in daily production of ethanol fuel to balance the supply of foreign gasoline used for blending. This reduction in ethanol production per day would significantly force an increase in ethanol (or fuel blend) prices. Evidently, E85 would be marked by increased price volatility in patterns similar to those demonstrated by foreign gasoline prices.

The highlight given above demonstrates some of the risks associated with ethanol fuel development where blending with foreign gasoline still has to be practiced. The next discussion demonstrates the effect of ethanol on gasoline.

2.4. Effects of Ethanol on Fuel Blends

Adding ethanol to gasoline creates new physical and chemical properties of the fuel blend. Based on an investigation to determine the suitability of ethanol/gasoline blended fuels containing 10vol% and 20vol% ethanol for non-automotive engines, Environment Australia (2002a; 2002b) has shown that ethanol significantly changes the properties of gasoline after blending. Prakash (1998) and others have highlighted that blending ethanol with gasoline affects the nature and quantities of exhaust, as well as the evaporative emissions from vehicles.

Changes in fuel properties are dependent on the amount of ethanol added to gasoline. These changes in fuel properties can affect the engine performance in various ways. The suggestion by Environment Australia (2002a, 2002b) that blending ethanol with gasoline changes the exhaust and evaporative emissions, fuel economy, operatibility, full load performance (power) and durability has been confirmed by other separate studies (http://www.fao.org/docrep/T440E/t4470e08.htm). Adding

10vol% and 20vol% ethanol in gasoline increases the oxygen content (% by weight) of gasoline from zero to 3.5 and 7.0 respectively (Environment Australia, 2002b) (Table 2.2). Plash blending without using a special blendstock has been assumed for these fuel changes.

Understanding the changes effected by ethanol fuel on gasoline is important in evaluating the technical issues when considering the use of blends higher than 10vol% ethanol in gasoline. This process is important when dedicated technologies would have to be developed or modifications of old car engines would have to be undertaken.

Table 2.2: Changes of gasoline properties when blended with ethanol.

Property	Gasoline	Ethanol	10vol% Ethanol/Gasoline Blend	20vol% Ethanol/Gasoline Blend[2]
Specific gravity at 15.5°C	0.72-0.75	0.79	0.73-0.76	0.735-0.765
Heating value (MJ/Litre) (BTU/lb)	43.5 18,700	27.0 11,600	41.9 18,000	40.0 17,200
Heating value (MJ/Litre) (BTU/gal)	32.0 117,000	21.3 76,000	30.9 112,900	29.9 109,000
Reid Vapor Pressure at 38.8°C (kPa)[1]	59.5	17	64.0	63.4
Stoichiometric Air/Fuel Ratio	14.6	9	14	13.5
Oxygen content (% by weight)	0.00	35	3.5	7.0

Source: Environment Australia, 2002b.

The resulting fuel properties after blending ethanol with gasoline include change in:

a. octane number,
b. volatility and Reid Volatility Pressure (RVP),
c. distillation curve,
d. enleanment,
e. fuel economy, and
f. water solubility and phase separation.

2.4.1. Octane number

Octane number is a measure of the resistance of a fuel to ignition, more often defined as a measure of the engine antiknock performance for gasoline or gasoline component (http://www.ec.gc.ca/transport/publications/ethgas/ethgas4.htm). The Research Octane Number (RON) and the Motor Octane Number (MON) are used to indicate that blending ethanol with gasoline results in an increase of the fuel octane from the base gasoline octane (Birrell, undated). Fuel ethanol has a high antiknock quality. The octane value for gasoline at the retail gasoline pumps is the average of the 'Research' (RON) and 'Motor' (MON) octane numbers (Prakash, 1998). Adding up to 10vol% ethanol in gasoline raises the fuel octane rating by 2.5-3 units, while 25vol% ethanol raises the octane rating by 8 units (Tables 2.3) (http://www.goodrichsugar.com/ethanol.asp). There is a significant scatter of RON and MON values suggested for ethanol. Nonetheless, there is a general consensus that ethanol has excellent antiknock properties, allowing higher compression ratios and improved engine efficiencies (Owen and Coley, 1995).

There are suggestions that ethanol-gasoline blends have superior resistance to combustion knock at low engine speed and deter run-on (the tendency of the engine to continue running after the ignition has been turned off) largely because of their higher heat requirement for their vaporization (Prakash, 1998).

Table 2.3: The effect of adding 10vol% ethanol in gasoline.

Property	Petrol	10vol% ethanol added
Boiling Point, °C	30-225	25-210
Net calorific value, (mass) K cal/Kg	10410	10026
Net calorific value, (vol) K cal/litre	7657	7394
Octane number	82-92	84-94
Stoichiometric air/fuel ratio (mass)	14.55	14.0
Heat of vaporization	95.7	111.2
Appearance	Colorless to light amber	Colorless to light amber

Source: http://www.goodrichsugar.com/ethanol.asp. Last update: September 18, 2004.

Table 2.4: Effect of ethanol addition on MON.

Source	Gasoline	MON	RON	% ethanol added	MON	RON
1	Regular	73	-	20%	81	-
2	Regular	83	92	10%	85	96
3	Regular	-	89	18%	-	97
	Premium	-	97	15%	-	102
4	ULP	-	92.9	30%	-	102.6

Source: Environment Australia, 2002b.

2.4.2 Effect of fuel volatility on vehicle performance

Fuel volatility can be described using the vapor pressure and the distillation curve, where each parameter is important in understanding the fuel efficiency (Environment Australia, 2002b). Inefficient volatility of gasoline may result in poor engine cold start, poor warm up driveability, and unequal distribution of fuel to the cylinders in carbureted vehicles. Gasoline that is highly volatile tends to vaporize very easily. It may even boil in fuel pumps, lines or in carburetors at high operating temperatures, stated Environment Australia (2002b) and Orbital Engine Company (2003a). When too much vapor is formed, a decrease in fuel flow to the engine may result.

Table 2.5: Effects of gasoline volatility on vehicle performance.

Volatility Too Low	**Volatility Too High**
1. Poor cold start	High evaporative emissions, canister overload and purge.
2. Poor warm up performance	Hot driveability problems, vapor lock.
3. Poor cold weather driveability	Fuel economy may deteriorate
4. Unequal fuel distribution in carbureted vehicles	
5. Increased deposits: crank case, spark plugs and combustion chamber.	

Source: http://www.ec.gc.ca/transport/publications/ethgas/ethgas4.htm

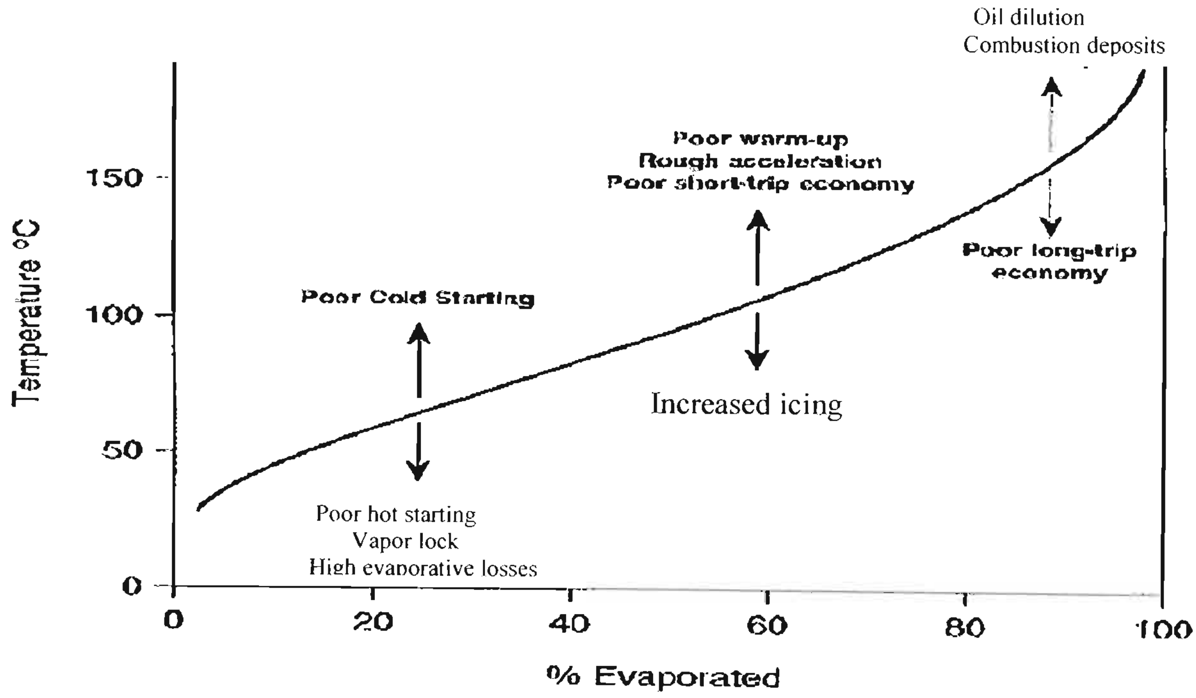


Figure 2.1. The effect of volatility on vehicle performance.

Source: Prakash, 1998.

2.4.3. Effect of ethanol on fuel volatility

While ethanol has a fixed boiling point, with a constant volatility, the volatility of gasoline can be tailored over a range by adjusting the relative amounts of different hydrocarbon components (Prakash, 1998). Adding ethanol to gasoline depresses the boiling temperature of the individual hydrocarbons. It also depresses the boiling points of the aromatic hydrocarbons slightly less that the aliphatic hydrocarbons, Prakash further indicated. Ethanol-gasoline blend (10% ethanol by volume in gasoline / E10) has significantly lower temperatures for evaporating the front-end hydrocarbons (more volatile fuel fractions). Fuel blends with ethanol higher than 10vol% have higher fuel volume evaporating under 200^0F, and the distillation curve for these blends would be lower than the curve of E10 (http://www.ec.gc.ca/transport/publications/ethgas/ethgas4.htm). Increasing ethanol concentrations beyond 10vol% in gasoline increases the fuel volume evaporating under 200^0F (Furey, 1985). Furey also indicated that the distillation curve for higher blends becomes lower than the 10vol% curve.

2.4.4. Reid vapour pressure

Vapour is another important parameter of gasoline that is affected by adding ethanol fuel. Owen and Coley (1995) indicated that increases in the Reid Vapour Pressure (RVP) of 6-8 kPa can be expected when 3vol% ethanol is added to gasoline with normal volatility. The Reid Vapor Pressure (RVP) of ethanol is significantly lower than that of gasoline. Blending ethanol with gasoline, however, forms a non-ideal solution that does not follow linear relationships. Instead of lowering the resultant RVP, low concentrations of ethanol in gasoline increase the fuel blend RVP (Furey, 1985). The behavior of the vapor pressure, while increasing the percentage volume of ethanol blended with gasoline, is rather anomalous. The fuel RVP peaks between 5 and 10vol% ethanol in gasoline and declines with ethanol concentrations higher than 10vol% in gasoline, Furey (1985) observed. At 20vol% ethanol fuel in gasoline, the RVP is around 5% higher than that of gasoline (Environment Australia, 2002b). Mixing ethanol fuel with a blendstock that has an RVP lower than that of ethanol can control the increase of the fuel blend RVP.

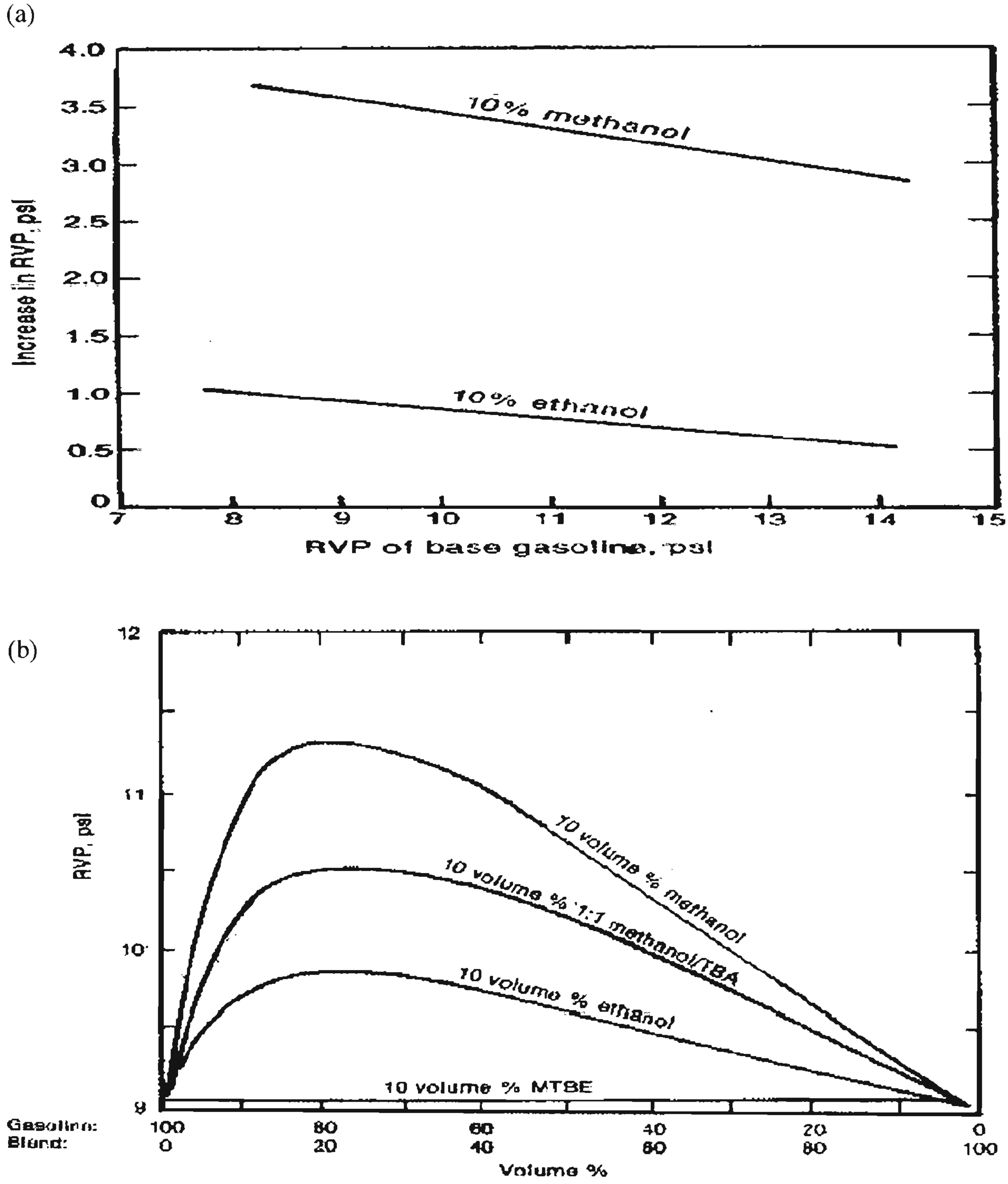


Figure 2.2: Effect of (a) base gasoline RVP on RVP increase due addition of ethanol, (b) commingling a gasoline and an ethanol blend of same RVP.

Source: Furey, 1985.

2.4.5 Driveability Index

In order to start a cold engine, there must be sufficient fuel in the vapor form present in the engine cylinders to initiate and sustain combustion. Increased RVP and lower front-end distillation temperature improve cold engine start for gasoline (http://www.ec.gc.ca/transport/publications/ethgas/ethgas4.htm). Ethanol/gasoline blends tend to behave slightly different from gasoline. Ethanol blends require more heat to vaporize than gasoline. The E10 fuel blend needs 16.5% more heat to vaporize completely than gasoline, asserted Prakash (1998). Important concerns resulting from blending gasoline with ethanol, indicated by Prakash, may include: (a) increased viscosity of ethanol-gasoline blends, which impede fuel flow, and (b) phase separation in the vehicle fuel system due to reduced solubility. Similar conditions can be expected during low fuel temperatures. Ethanol concentrations higher than 10vol% in gasoline reduces the temperature for Vapor/Liquid Ratio (V/L) of 20, which may increase the likelihood of vapour lock (Prakash, 1998).

2.4.6. Enleanment effect on ethanol

It is well known that gasoline is a mixture of many hydrocarbon compounds consisting only hydrogen and carbon. The exact ratio of air-to-oxygen required to completely burn fuel to carbon dioxide and water is called its ‘stoichiometric air-fuel ratio’. Since ethanol fuel contains oxygen and fewer carbons, less air is needed for complete combustion of ethanol-gasoline blends than for gasoline. A blend containing 10vol% ethanol, for example, needs 14.0-14.1 pounds, while gasoline would need 14.7 pounds of air for complete combustion of one pound of fuel (http://www.ec.gc.ca/transport/publications/ethgas/ethgas4.htm). Switching between oxygenated and non-oxygenated fuels, whether or not a vehicle uses a ‘closed-loop’ fuel control system, does not affect the drivability characteristics of the vehicle (Prakash, 1998).

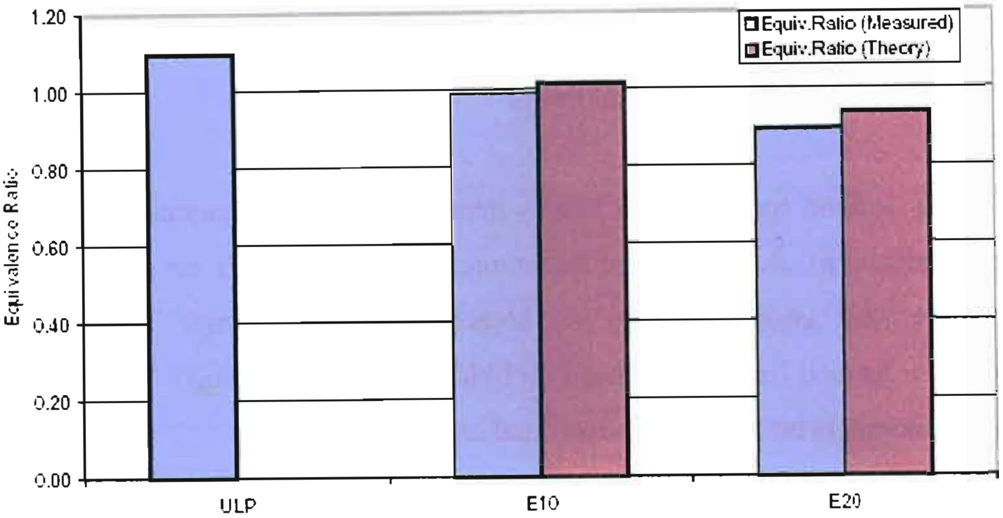


Figure 2.3: Comparison of the utility engine enleanments for unleaded gasoline (ULP), E10 and E20 fuel.

Source: Orbital Engine Company, 2003a.

Orbital Engine Company (2003a) compared the theoretical enleanment associated with the presence of variable ethanol percentages in fuel blends with measured results at one point during engine power tests. Results showed a reasonably good correlation between measured and theoretical equivalence ratios for E10 fuel blend. The conclusion was different with E20 (i.e. 20vol% ethanol mixed with 80vol% gasoline), as the correlation failed to match that of E10 fuel. In the case of E20, the measured results showed more enleanment than expected.

2.4.7. Water solubility phase separation

Non-oxygenated gasoline requires very a small amount of water before phase separation occurs. Ethanol has a higher affinity for water (Ulrich, 1999). Thus, ethanol-gasoline blends can absorb significantly more water without phase separation occurring than gasoline. If too much water is introduced into an ethanol-gasoline blend, the water and most of the ethanol would separate from gasoline. The amount of water that can be absorbed by ethanol-gasoline blends without phase separation varies from 0.3 to 0.5% by volume, depending on temperature, aromatics and ethanol content (http://www.ec.gc.ca/transport/publications/ethgas/ethgas4.htm).

The E10 blend is no more susceptible to phase separation than non-oxygenated gasoline.

2.5. Effect of Ethanol on Fuel Economics

The demand for ethanol is largely dependent on the economics of the fuel. Current indications show that the economics of ethanol as a car fuel are less competitive with gasoline (Table 2.6). Hence, the core challenge is growing an ethanol fuel demand based on reduced fuel-blend costs to consumers (i.e. providing greater economic benefits to automakers and car owners).

Besides the limited fuel economy of ethanol to the consumer, the Renewable Fuels Association (2000) indicated the U.S. economic benefits of ethanol fuel as follows:

(a) industry operations and spending for new construction contributed about US$1.14 billion in Federal tax revenue and $734 million to state and local governments in 2004 (http://www.ethanolrfa.org/Economic_Contribution_2004.PDF),

(b) production reduces the taxpayer burden for unemployment benefits and farm deficiency payments,

(c) combination of spending for annual plant operations and capital spending for new plants under construction was projected to create nearly $14 billion in gross output for the U.S. economy in 2004,

(d) increased economic activity and new jobs could have put an additional $3.5 billion into the pockets of American consumers in 2004,

(e) reduces the consumer cost of gasoline by extending supplies, providing an alternative to costly imported oil and leverage for independent gasoline marketers to compete against the larger, more powerful integrated oil companies,

(f) study showed that increasing production to 5 from the current 3.2 billion gallons would annually create 214,000 jobs, $5.3 billion in new investment in renewable fuel production facilities, and increase household income by $51.7 billion (http://www.ethanolrfa.org/combined_AUS_Report.PDF),

Table 2.6: Ethanol fuel blend (E85) economy for the U.S. A. flexible fuel vehicles (FFV).

Fuel	Car model	Vehicle type	Emission class	Powertrain	Fuel capacity[1]	Range[2] (miles)	Annual Fuel costs[6] (US$)
E85 FFV	Dodge Ram 1500 Series	Pickup	Tier II Bin 10A	4.7L V8	26 GGE	416	-
E85 FFV	Chrysler Sebring[4], Dodge Stratus[4]	Sedan	Tier II Bin 8	2.7L V6	16GGE	300	E85: 1,323
E85 FFV	Ford Taurus[4]	Sedan Wagon	ULEV	3.0LV6	18 gallons	-	-
E85 FFV	Ford Explorer 4WD[4], Explore Sport Trac[4], Mountaneer[4]	SUV	LEV	4.0L SOCH V6	22.5 gallons	250-350[5]	E85: 1,730; Gas: 1,168
E85 FFV	Chevy Tahoe [4], GMC Yukon[4]	SUV	Tier II Bin 10	5.3LV8	26 gallons	260-338	E85: 1,874; Gas: 1,312
E85 FFV	Chevy Suburban [4], GMC Yukon XL[4]	SUV	Tier II Bin 10	5.3L V8	32.5 gallons	309402	E85: 1,874; Gas: 1,401
E85 FFV	Chevy Silverado[4], GMC Sierra	LD Pickup	Tier II Bin 10	5.3 V8	34 gallons (long box)	327-392 (long box)	E85: 1,874; Gas: 1,312
E85 FFV	Mercedes-Benz USA: C320 Sedan, Wagon, Sport Coupe	Sedan, Wagon, Sport Coupe	LEV	90-degrees V6	16.4 gallons	293-441	E85: 1,406 Gas: 1,092

Notes:

[1] CNG and LPG vehicles fuel capacity based on slow fill @ 3600 psi.; [2] Estimated Range on alternative fuel and based on fuel capacity. For EVs, range depends on battery type.; [3] Hybrid electric vehicles are considered advanced technology vehicles, not AFVs.; [4] All E85 vehicles are considered flexible fuel vehicles (FFVs).; [5] This information has not been confirmed.; [6] Annual fuel cost is based on travelling 15,000 miles per year at an average fuel cost of $1.40 for gasoline, $1.50 for E85, $0.90 for CNG and $1.40 for LPG. Figures shown represent fuel costs for models with automatic transmission.

Glossary

LEV = Low Emission Vehicle; E85 = 85% Ethanol, 15% Gasoline; FFV = Flexible Fuel Vehicle; GGE = Gasoline Gallon Equivalent

Source: Alternative Fuel Vehicles, 2004/2005.

(g) the U.S.A. ethanol tax credit is provided to gasoline marketers and oil companies, not to ethanol producers, as an incentive to blend their gasoline with clean, domestic, renewable ethanol (i.e. it is a cost-effective program that actually returns more revenue to the U.S. Treasury than it costs, due to increased wages and taxes and reduced unemployment benefits and farm deficiency payments, while at the same time holding down the price of gasoline and helping the American farmer).

The U.S.A. has subsidized the oil industry since the early 1900s and continues to do so. Based on the indications of by General Accounting Office in an October 2000 report, the oil industry received over US$130 billion in tax incentives just in the past 30 years or so, dwarfing the nearly US$11 billion provided for renewable fuels (Renewable Fuels Association, 2000). During this period, U.S. oil production has plummeted while annual U.S. ethanol production has grown by over 2 billion gallons. (http://www.gao.gov/. Direct local economic benefits are minimal in many oil-importing countries.

2.6. Environmental Implications of Fuel Ethanol

Environmental implications of ethanol fuel are now well understood. Apace Research Ltd (1998), Roarty and Webb (2003), and others have made the impression that key environmental issues driving the use of ethanol blended gasoline vis-à-vis conventional gasoline include:

(a) unlike the production of gasoline from refined crude oil (i.e. a resource with finite deposits), ethanol production from agricultural crops is regarded as renewable, and

(b) reduced tailpipe emissions of carbon monoxide, hydrocarbons, 1-3 butadiene, benzene, toluene, xylenes and reduced full fuel lifecycle emissions of greenhouse gases.

Detailed analyses of ethanol environmental and health benefits have been undertaken during the last decade (see Armstrong, 1999; Ulrich, 1999). A summary of these benefits is given below.

2.6.1. Environmental distribution

Ethanol is completely miscible with water. Considering that the miscible and accumulation properties of Methyl Tetra-Butyl Ether (MTBE) in groundwater led to phasing out of this fuel additive in the U.S.A., concerns over similar experiences have been shown (Ulrich, 1999). Ulrich assumed that a better apprehension of the occurrence and persistence of MTBE in the environment (especially in groundwater aquifers) would provide important understanding of other gasoline oxygenates for which there is still insufficient scientific information about their environmental behavior. Similar conclusions are likely to be made in relation to all octane-enhancing products when they are extensively used (Environment Australia, 2000). In static systems where gasoline is allowed to equilibrate with water, concentration of ethanol is dependent on the water-to-fuel volume ratio, Ulrich (1999) highlighted. Nevertheless, should ethanol be released to groundwater from any source, it is expected to rapidly biodegrade given its half-life of 4.1 days (unlike MTBE having a half-life greater than 120 days) (Environment Australia, 2000; Ulrich, 1999). Table 2.8 illustrates the half-life variation between different oxygenates. Ethanol does not bioconcentrate or adsorb to sediments, claimed Ulrich (1999) and Environment Australia (2000).

Based on the assertion that abiotic oxidation of organic contaminants in the subsurface generally does not occur to an appreciable extent, it is therefore not expected to contribute to the loss of ethanol from ground contaminated groundwater (Ulrich, 1999). Hence, the volatilization of ethanol from subsurface spills into the unsaturated zone would be limited, because ethanol is expected to leach relatively fast into groundwater. Because of its high aqueous solubility and low partitioning from the liquid to gaseous phase, Ulrich (1999) suggested that substantial losses of ethanol through volatilization once mixed with groundwater are unlikely. The opposite however is expected when ethanol from gasoline comes in direct contact with the air, given that ethanol is an important component of the evaporative emissions released from ethanol/gasoline fuel blends (see previous sections).

During the half-life, ethanol accumulation in the soil and groundwater can be a factor of the microbial activity. Since microorganisms capable of degrading ethanol are ubiquitously distributed in the environment, ethanol biodegradation would not be limited by the availability of the requisite microorganisms (Ulrich, 1999). Although ethanol can be toxic to microorganisms at (differentially) high concentrations, it is freely permeable across the cell membrane and partitions within the cytoplasm, including the inner hydrophobic core of the membrane, Ulrich further indicated.

2.6.2. Ethanol and vehicle emissions

With the exception of E85 and E20, information on vehicle emissions associated with burning higher ethanol fuel blends than E10 is still limited (Environment Australia, 2002a). More recently, vehicle emission tests for E20 (i.e. 20vol% ethanol blended with 80vol% gasoline) have been undertaken in Australia (Orbital Engine Company, 2003a; 2003b; 2004).

Various parameters affect the characteristics of vehicle emissions when ethanol fuel blends are used. Prakash (1998), for example, demonstrated the sensitivity of motor vehicle emissions to changes in air-fuel ratio. Orbital Engine Company (2003b), Prakash (1998) and others indicated that air-fuel rations slightly leaner than the stoichiometric maximum emissions of oxides of nitrogen (NOx) and minimal emissions of hydrocarbons (HC) (Fig.2.5).

The effect of oxygenated blends on exhaust emissions can be summarized as indicated below (Bykowski and Garbe, 1981; Naman and Allsup, 1980):

(a) ethanol/gasoline blends reduce CO and HC emissions,
(b) ethanol blends increase tailpipe emissions of NOx,
(c) based on the Coordinating Research Council (CRC) study (Brinkman *et al*, 1975), ethanol emissions represent a very small amount (0.0065 gram ethanol per mile) of the total hydrocarbons in the exhaust emission,
(d) ethanol blends reduce tailpipe toxins, benzene, and 1-3 butadiene, and
(e) fuel blends containing ethanol lead to increased tailpipe emission of acetaldehyde compared to gasoline.

Table 2.8: The half-life of oxygenates.

Oxygenate	**Rate of degradation (ppm C-day^{-1})**	**Oxygenate**	**Rate of degradation (ppm C-day^{-1})**
Alcohol		**Ethers**	
Methanol	7.4	Methyl Tetra-Butyl Ether	0
Ethanol	17.9	Methyl Tetra Amyl Ether	0
2-propanol	7.6	Ethyl Tetra Butyl Ether	0
Tert-butanol	0	Isopropyl Ether	0
		Diethyl Ether	0
Esters		Propyl Ether	0
Ethyl acetate	16.6	Butyl Ether	0
Methyl propionate	7.3	Butyl Methyl Ether	0.5
Methyl isobutyrate	4.1	Butyl ethyl Ether	0
		Ketones	
		Methyl Ethyl Ketone	9.4
		Acetone	7.3
		Methyl Isobutyl Ketone	21-28

Source: Suflita and Mormille, 1993 (cited in Ulrich, 1999).

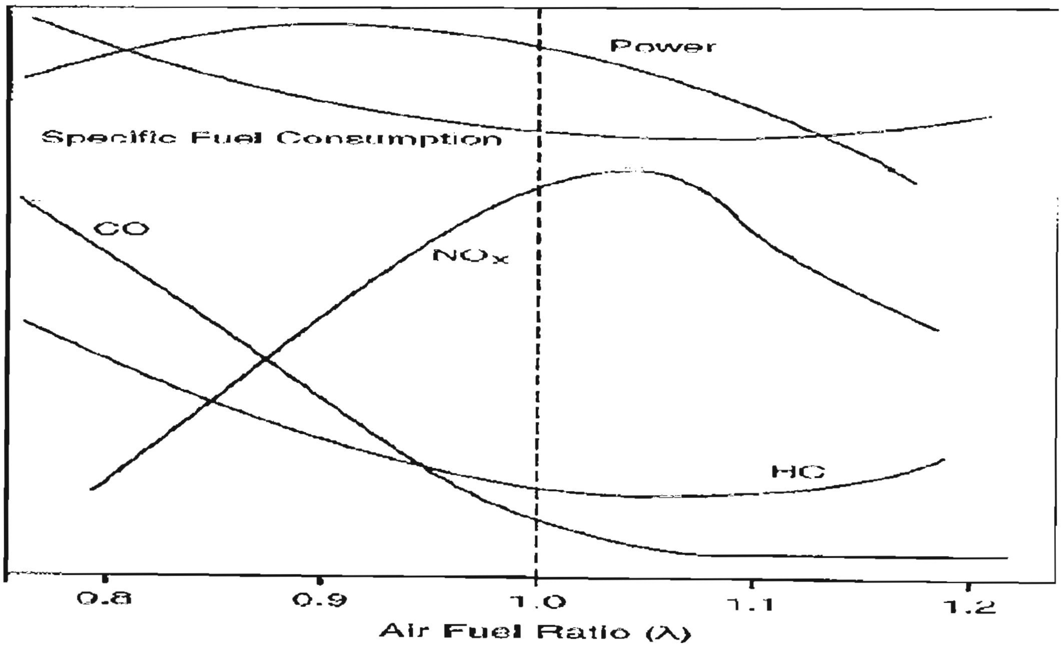


Figure 2.5: Effect of air-fuel ratio on exhaust emissions.

Source: Prakash, 1998.

2.7. Drivers of Global Bio-Ethanol Fuel Development

Generally, the drivers of bio-ethanol fuel development fall in three categories. Firstly, bio-ethanol fuel development has important socio-economic benefits for rural people. Locally, the industry can contribute to economic growth and development, leading to greater consumption of natural stock in various ways per capita. Countries producing bio-ethanol fuel are less dependent on foreign fuels (Berg, undated). Bio-ethanol fuel can be blended with gasoline in various proportions to run petrol cars. All car manufacturers in the world accept bio-ethanol fuel blends of up to 10vol% in 90vol% gasoline (http://www.e10unleaded.com/technician.htm). Therefore automakers provide warranties for cars using these bio-ethanol-gasoline blends (http://www.iogen.ca/3100.html). Dedicated technologies designed to run on higher bio-ethanol fuel blends are already available in global markets. Blending 85vol% bio-ethanol fuel with gasoline is considered as an important strategy leading to a reduction in local dependence on foreign fuels (Hunter, 2004). Internationally, central governments have in recent created fuel policies that promote bio-ethanol fuel production, competitive pricing and market development (Berg, undated; http://www.e85fuel.com/news/073004fyi.htm; http://www.iogen.ca/3200.html). General Motors, Ford Motors and many other automakers are increasing the production of cars dedicated to run on E85 fuel blends (http://www.arifleet.com/2004_AFV.htm. Reducing the conversion costs of lignocellulose to ethanol fuel is considered as the next important drive for bio-ethanol fuel development around the globe, as the fuel consumer prices will fall significantly lower than for gasoline.

2.8. Bio-Ethanol Fuel Demand

The demand for bio-ethanol fuel is a function of the local demand for gasoline. Because of greater human development per capita, energy will always define human consumption rates, as well as trajectories of natural stock depletion and certainly not the opposite. Characterized by the infinite upper limit, development per capita creates an infinite demand for energy consumption (see Chapter Eight). Hence the potential demand for bio-ethanol fuel will always exist, while still humanity consumes energy during development. Without policies and regulations, economics become the factor defining the upper limit for bio-ethanol fuel consumption among the rich people, while defining the opposite for the poor segment of the world's human population.

Comparing bio-ethanol fuel with gasoline is certainly inappropriate and irrational given the current commercial development attained by different fuels. Nevertheless, bio-ethanol fuel may serve locally desirable energy goals, but it is relatively more expensive to produce and also faces unfavorable opportunity cost structures (Berg, undated; California Energy Commission, 2004). Government incentives and subsidies are the core drivers for successful creation and development bio-ethanol fuel demand in all sections of the world (Brown, 2004; http://www.e85fuel.com/news/073004fyi.htm). Production cost incentives and subsidies for bio-ethanol fuel development comprise of support in feedstock price, capital cost, as well as income tax concessions, while income enhancing incentives consists of excise tax concessions, guaranteed captive markets, price guarantees and direct price support (http://www.meti.go.jp/report/downloadfiles/g30819b40j.pdf). With these supporting mechanisms, Brazil has become the world's largest producer of bio-ethanol fuel (Fig.2.7) followed by the U.S.A. with major economic savings (Berg, undated; Ethanol Across America, 2004; Moreira and Goldemberg, 1999). In the U.S.A., bio-ethanol fuel production mainly from corn was estimated at about 3.2 billion gallons (12.112 litres) by the end of 2004 (Ethanol Across America, 2004). According to Berg (undated), the southern African region will become a major exporter of bio-ethanol fuel to Europe, Japan, U.S.A. and other countries in the next few years.

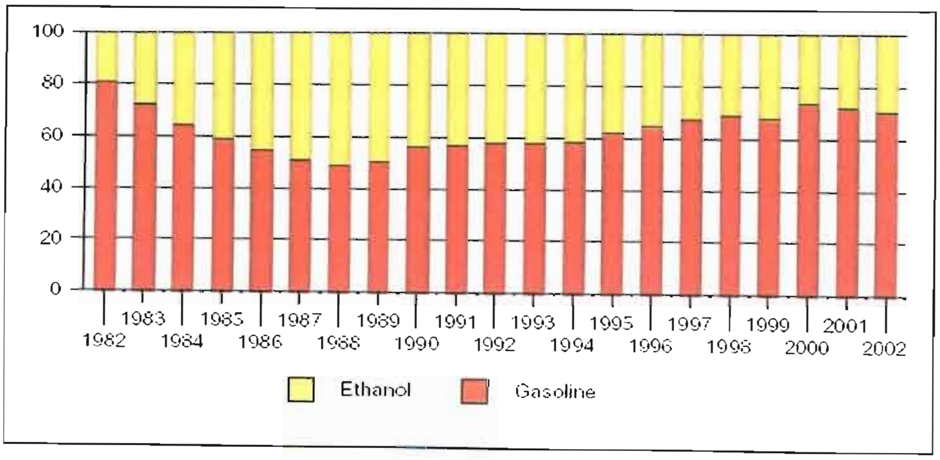


Figure 2.7: Ethanol production in Brazil.

Source: http://www.meti.go.jp/report/downloadfiles/g30819b40j.pdf

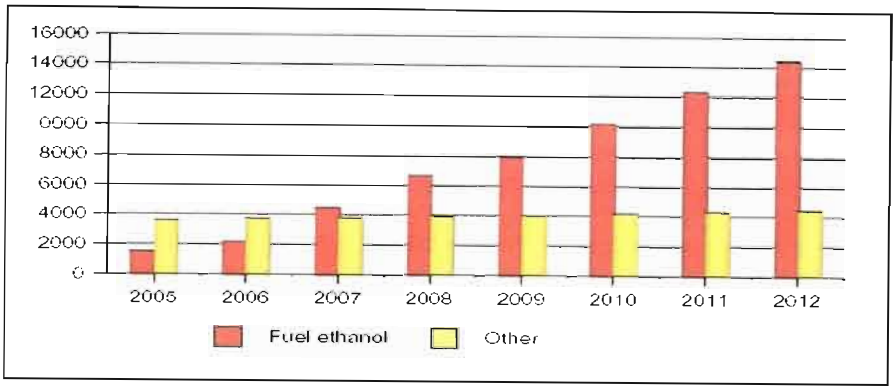


Figure 2.8: World ethanol imports for fuel, beverage and industrial uses.

Source: http://www.meti.go.jp/report/downloadfiles/g30819b40j.pdf

2.9. Summary and Conclusion

The discussion given to this far has shown that ethanol can be used as a transport fuel. With the exception of Brazil where pure fuel ethanol is used to run dedicated motor technologies, the global demand for fuel ethanol is mainly for blending with gasoline. The importance of energy security in developing bio-ethanol fuel has been given serious consideration in many countries around the world, in addition to the associated environmental benefits of this fuel. Quite recently, important developments of higher bio-ethanol fuel blends in the U.S.A. offer greater hope for local energy security in the world's transport industry. Using fuel blends to promote and develop bio-ethanol as a fuel creates serious economic risks for local industries, particularly for countries that still import gasoline used for blending.

Before describing the methodology used during this investigation in Chapter Four, a brief evaluation of specific sources of bio-ethanol fuel is presented in Chapter Three.

Chapter Three

Analyses of Bio-Ethanol Feedstock

3.0 Introduction

Examining ethanol as a transport fuel has been the focus of the discussion presented in the Chapter Two. Drawn form the discussion is that using ethanol fuel blends in cars dedicated to run on gasoline holds differential benefits. Also highlighted in the previous chapter is that much of the world's growing interest is on using up to 10vol% ethanol in gasoline. Attention has been further drawn to the serious limitations of lower ethanol fuel blends. Nonetheless, the global efficiency in exploiting the advantages of lower ethanol fuel blends has led to the current success of the industry. In the U.S.A., for example, E10 has simplified the introduction of the E85 fuel blend, much more as a result of the increasing consumer preference for bio-ethanol fuel than influenced by Government legislations (see Fabi, 2004).

Current observations show the importance of feedstock for successful development of bio-ethanol fuel worldwide. Based on this observation, evaluating bio-ethanol fuel feedstocks having greater potentials for successful development in southern Africa is the principal purpose of this chapter. The process is achieved by:

(a) analyzing agricultural crops with greater potentials for intensive development,

(b) characterizing the economics of developing ethanol feedstock, and the potential implications for the industry as a whole, and

(c) demonstrating the total implications of intensive bio-ethanol development.

3.1. Feedstock Characterisation

While the world's attention for bio-ethanol fuel development increases, agricultural feedstock costs significantly incapacitate the widespread use of this fuel worldwide. The use of ethanol fuel as the secondary market for agricultural crops tremendously impacts on ethanol fuel costs. These impacts become greater in poor and developing sections of the world (see Section 3.3). Hence the evaluation given in this section requisites the analysis of comparative agricultural feedstock types. Based on this assertion, ethanol sources analyzed include: (a) corn (maize), (b) sweet sorghum, (c) sugar cane, and (d) lignocellulose.

3.1.1. Corn and sorghum feedstocks

Corn (maize) ethanol accounts for an important share of the world's total ethanol fuel. Corn and wheat are the major sources of starch for ethanol production (Badger, 2002). More recent estimates suggest that starch crops account for about 39% of ethanol produced worldwide (http://www.meti.go.jp/report/downloadfiles/g30819b40j.pdf). Over the last few years, ethanol produced from corn starch has increased tremendously in some parts of the globe. In the U.S.A., for example, of the nearly 3.2 billion gallons of fuel ethanol currently produced, about 90% is derived from corn starch (Berg, undated, Brown, 2004).

Future growth of global ethanol fuel production will have important influence on the trajectories of corn production. According to Dobermann and Cassman (2002), nearly 30 million hectares of corn are harvested annually for grain in the U.S.A. where eleven states along the Corn Belt produce in excess of 210 million tons (or 35% of the world's corn supply). Although progressive farmers routinely harvest 160-220 bushels per acre (10-14 tons per hectare), average corn yields are close to 140 bushels (i.e. 371 gallons (or 1404 liters) of ethanol) per acre (8.8 tons per hectare (i.e. 3300 liters of ethanol per hectare) (Berg, Undated; Dobermann *et al.*, 2002). These corn yields determine not only the output of ethanol fuel per unit area of land, but also have important influence on the economics of corn ethanol fuel. The latter assertion therefore identifies the major challenge to ethanol fuel producers of lacking control over corn prices at the farm gate (see sections 3.2, 3.3 and 3.4). Increasing the output of high-value products per bushel of corn has become the most common strategy toward improving the economic efficiency of ethanol fuel derived from corn feedstock (Fig. 1).

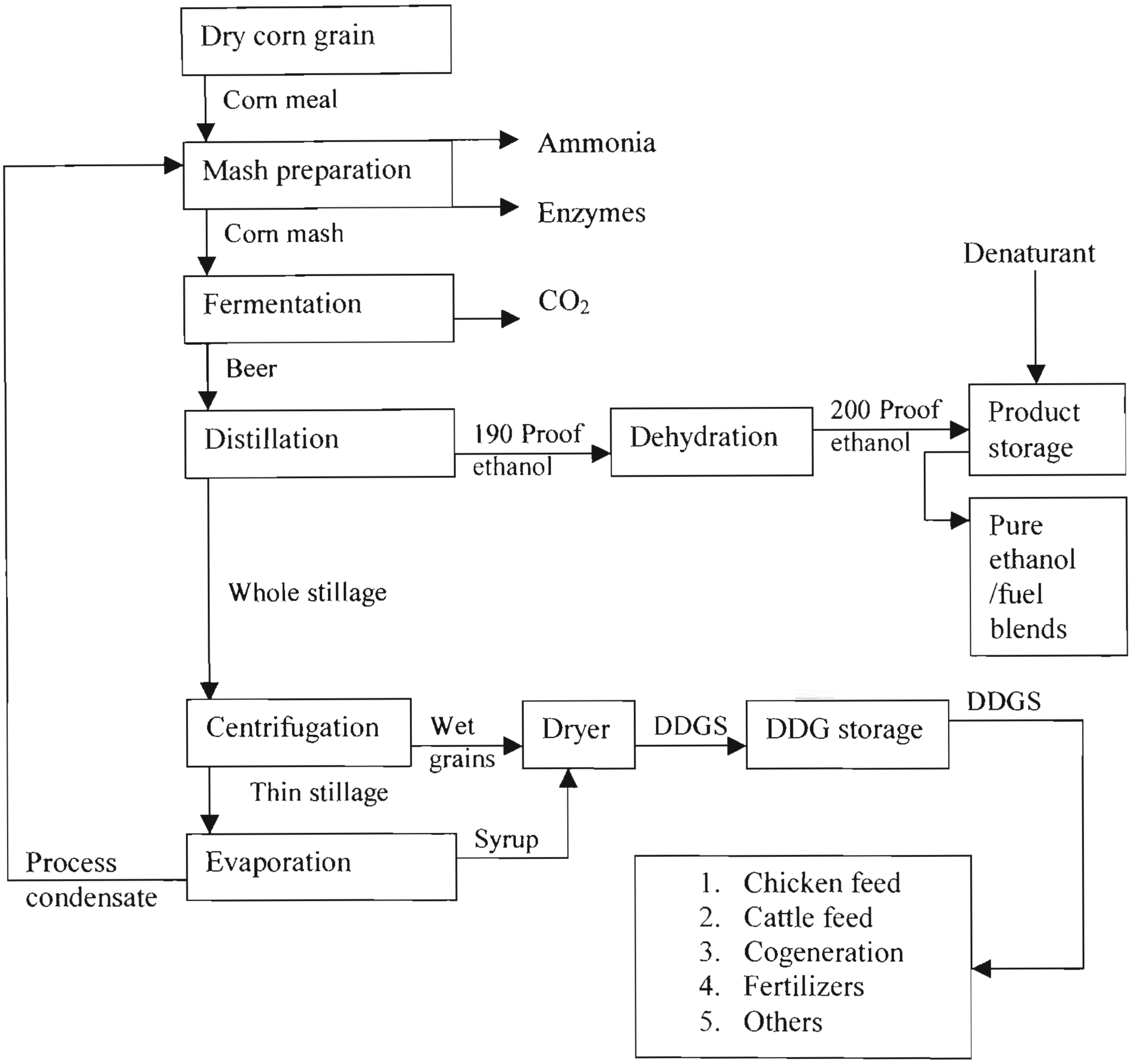


Figure 3.1: Illustration of the corn (maize) dry-mill process.
Adapted from Ashworth (Undated).

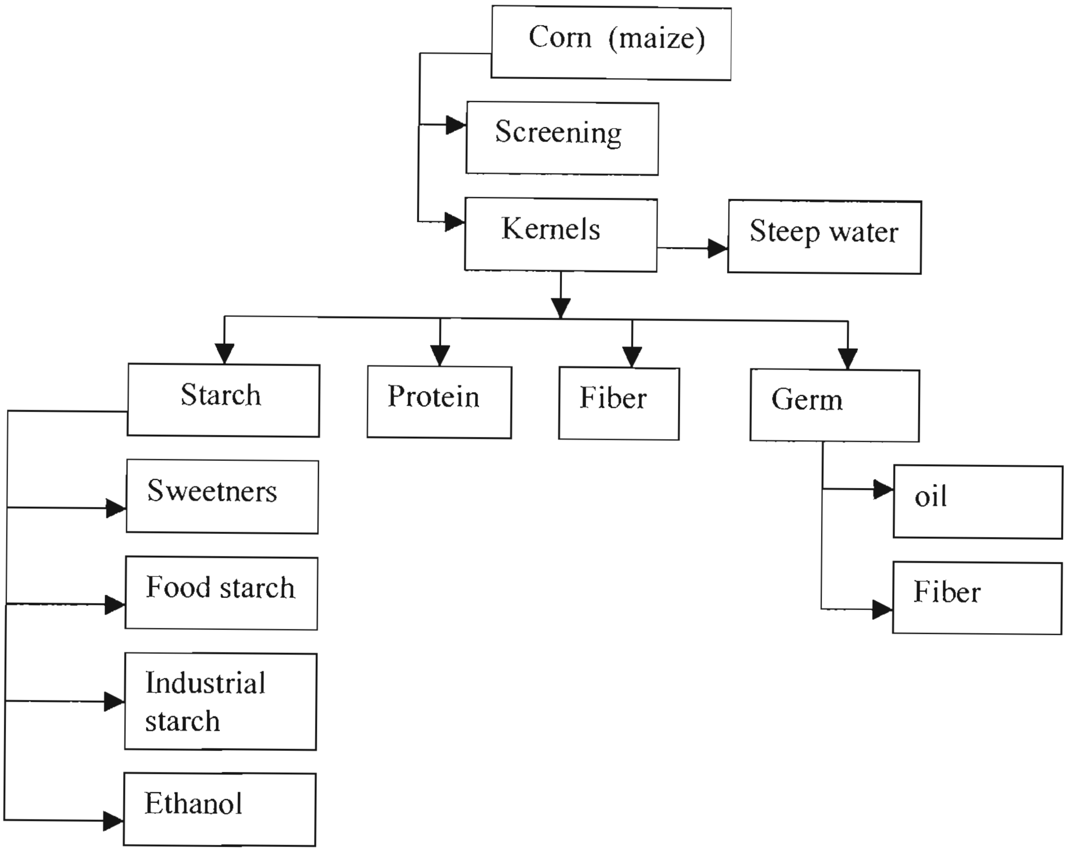


Figure 3.2: The conversion process of corn to ethanol using the wet-mill technology.
Source: Ashworth, undated.

3.1.2. Corn conversion efficiency

Fuel ethanol producers focus on attaining maximal ethanol yields from a bushel of corn. The conversion efficiency of corn feedstock improved over decades of technology development. Prior to the early 1980s, Madson and Monoceaux (Undated) stated that one bushel of corn produced 2.375 gallons (8.989 liters) of motor fuel grade ethanol (MFGE). Although the yield of 2.5 gallons per bushel of MFGE was the rule of thumb in the industry for many years, Coltrain (2001), supported by Ashworth (Undated) and Madson and Monoceaux (Undated), stated that fuel ethanol yields as high as 2.8 gallons per bushel can be achieved based on more recent technology developments. While ethanol yields per unit corn mass have increased since the early

1970s, the opposite holds for the parameters associated with the conversion of corn to absolute ethanol (Figure 3.3)

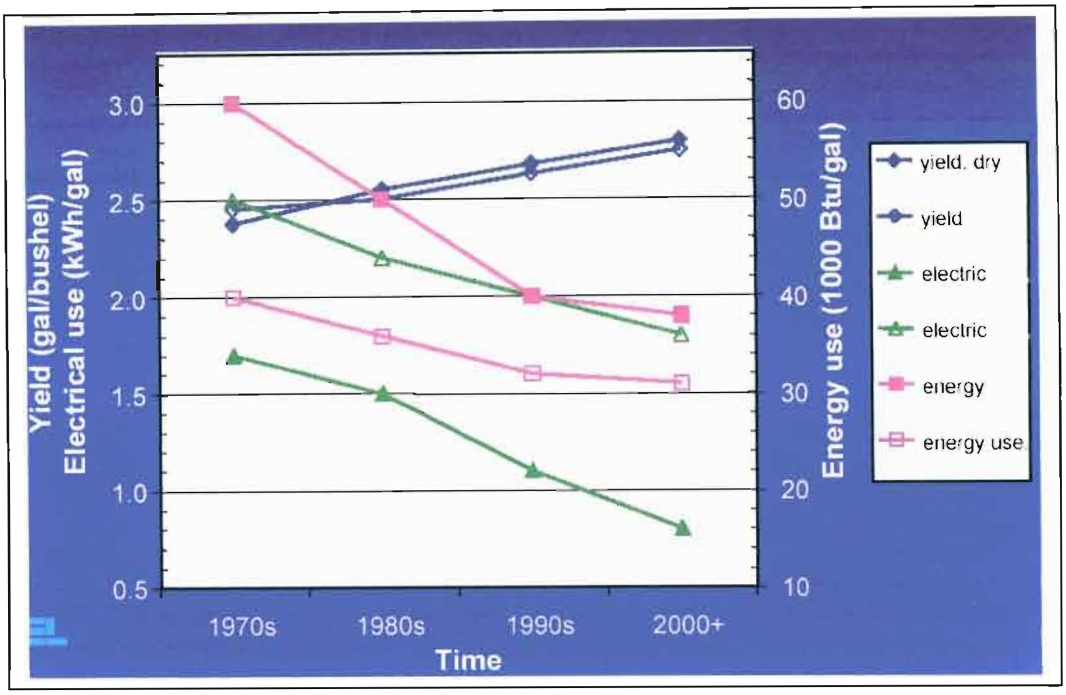


Figure 3.3: Effects of efficiency improvement on corn ethanol production.
Source: Ashworth, undated.

Grain sorghum is another important source of starch for ethanol production. India is the world's second largest producer of sorghum, with annual average yields fall between 10 and 11 million tons of 12 million hectares of land harvested (Sheorain, *et al.*, 2000). Sheorain *et al.* further indicated that typical fermentation of grain sorghum (containing 60% starch) would produce in excess of 360 liters (95.112 gallons) of ethanol per ton, with a conversion efficiency of 85%. Included in the highlight made by Sheorain *et al.* has been the suggestion that under optimal processing, sorghum has the potential of producing 380-390 liters of absolute alcohol per ton of grain. Like in the case of corn processing, fermentation of grain sorghum to ethanol produces the dried residue called Distiller's Dried Grain and Solubles (DDGS), which are excellent ingredients for animal feed. Grain sorghum has a higher yield potential for absolute ethanol per unit mass than corn (Table 3.1).

Table 3.1: Characterization of absolute ethanol potentials from grain sorghum and corn.

Component	**Content (%)**	
	Sorghum	Corn
Starch	63-68	60-64
Moisture	9-13	8-11
Proteins	9-11	9-11
Fats and oils	1-1.5	3-5
Crude fiber	1.5-2	1.5-2
Ash	1-2	1.2
Other organics	8-12	7-9

Source: Sheorain *et al.*, 2000.

Generally, parameters characterizing corn as a feedstock for ethanol may be common with the other feedstock types. Sweet sorghum can be used to evaluate the general efficiency of corn as a dedicated feedstock for ethanol fuel production.

3.2. Sugarcane, Sweet Sorghum and Sugar Beet

Sugar accounts for most (61%) of fuel ethanol produced in the world (Berg, undated). In 1993, there were more countries producing ethanol fuel from sugar crops such as sugar cane and sugar beet (Fig. 3.5a). However, ethanol fuel production from sugar crops has showed downward trends during the opening of the new millennium (Fig.3.5b). This decline has been effect by the falling demand for hydrated ethanol fuel in Brazil where cane sugar is the source of fuel ethanol (Boiling Suarez, 2001; Moreira and Goldemberg, 1999). Despite the recent decline in the world's ethanol fuel production from sugar, Brazilian sugar cane continues to have an important influence on global trends of ethanol fuel production. Current declines of the world's sugar prices favor an increase in ethanol fuel production from sugar crops like sugar and sugar beet. As a result, more countries are expected to be important producers of fuel ethanol derived from these sugar crops in the next few years (Fig. 3.6a).

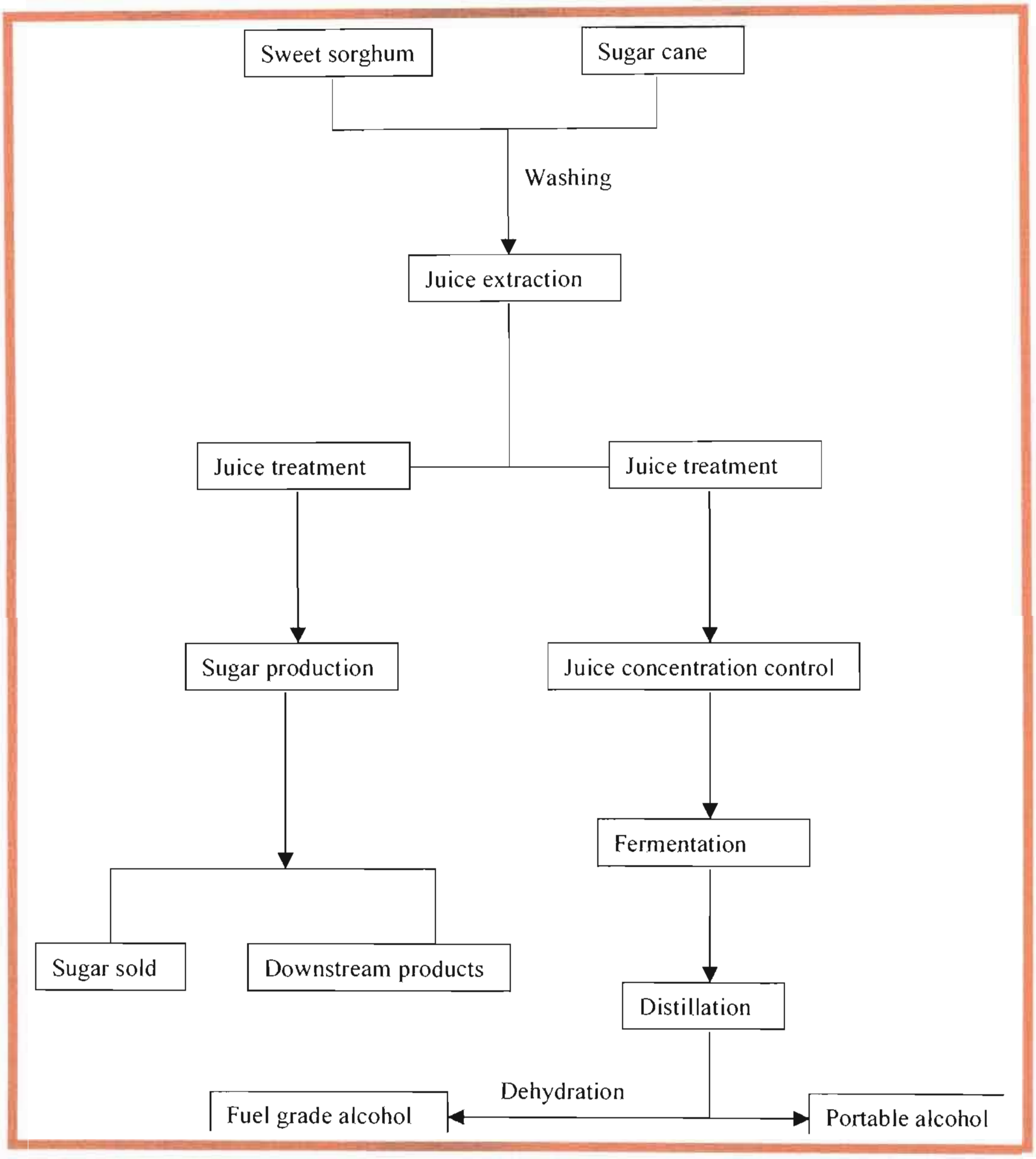
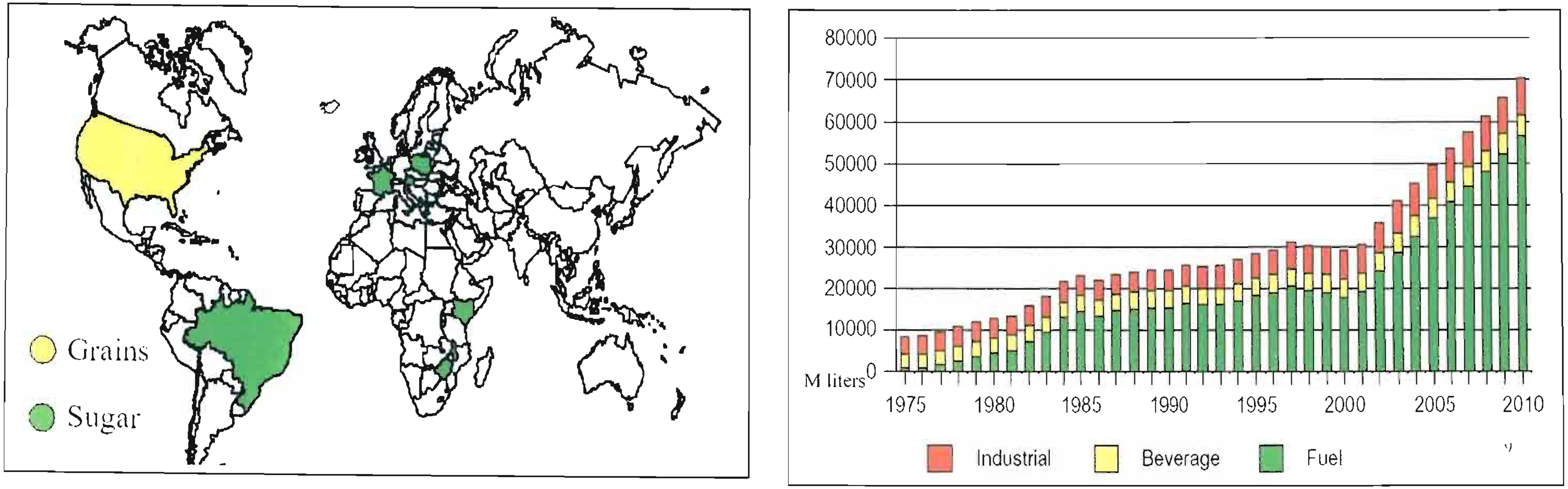


Figure 3.4: Production route of sweet sorghum (sugar cane) fuel grade alcohol.



(a) (b)

Figure 3.5: World fuel ethanol production (a) in 1993, (b) trends by type.

Source: http://www.meti.go.jp/report/downloadfiles/g30819b40j.pdf

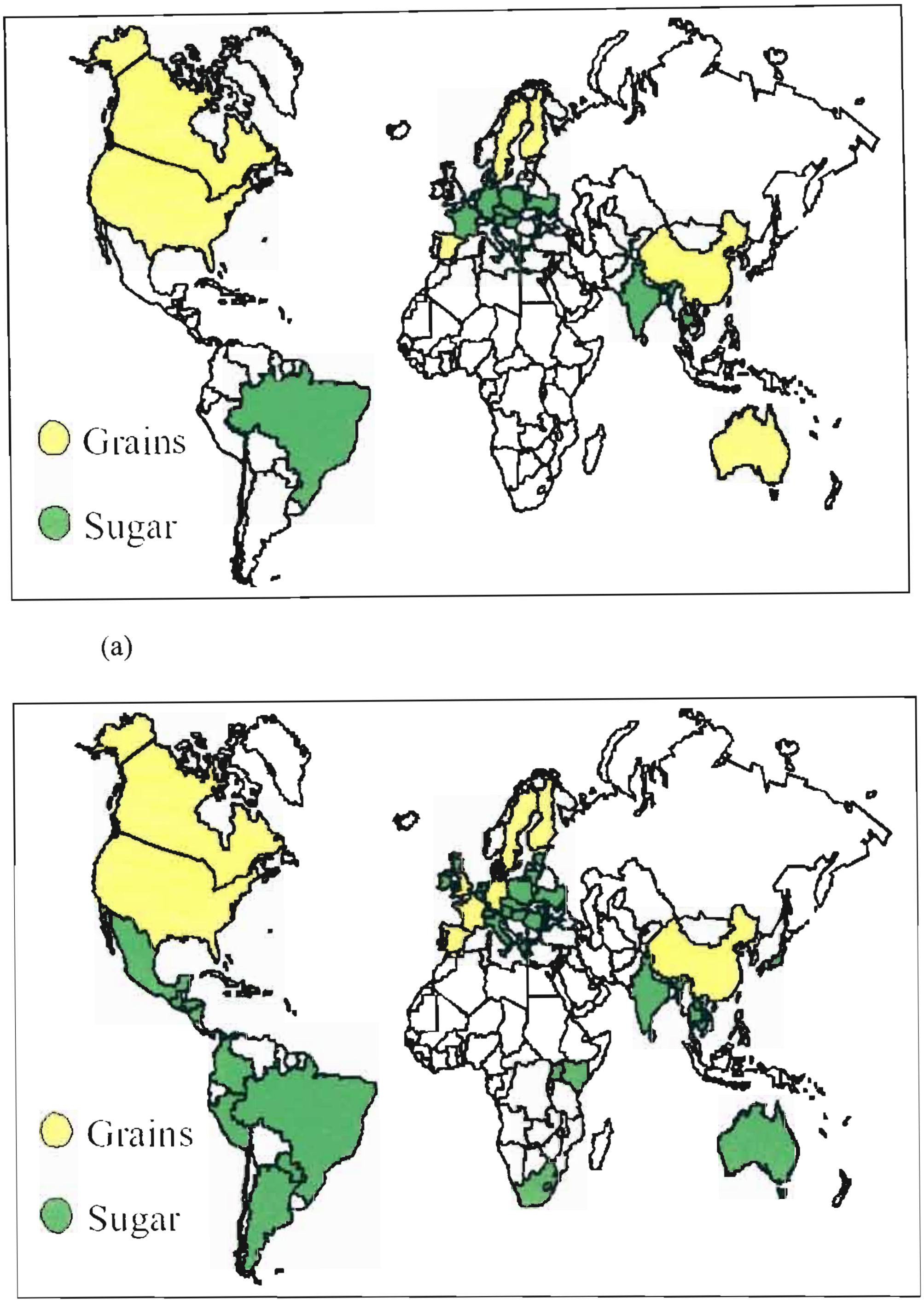


Figure 3.6: Indications of global fuel ethanol production in (a) 2003, (b) 2013.
Source: http://www.meti.go.jp/report/downloadfiles/g30819b40j.pdf

Global changes in sugar prices call for improved efficiency in the sugar beet industry. Investigations have been initiated to understand the efficiency of sugar beet resources for ethanol production (Labor and Economic Growth, 2000; Peterson *et al.*, 2003). Estimates show that 12.8600 tons of sugar beet can produce 1 ton of ethanol and 0.75 ton of (9% moisture content) animal feed (Fig.3.7).

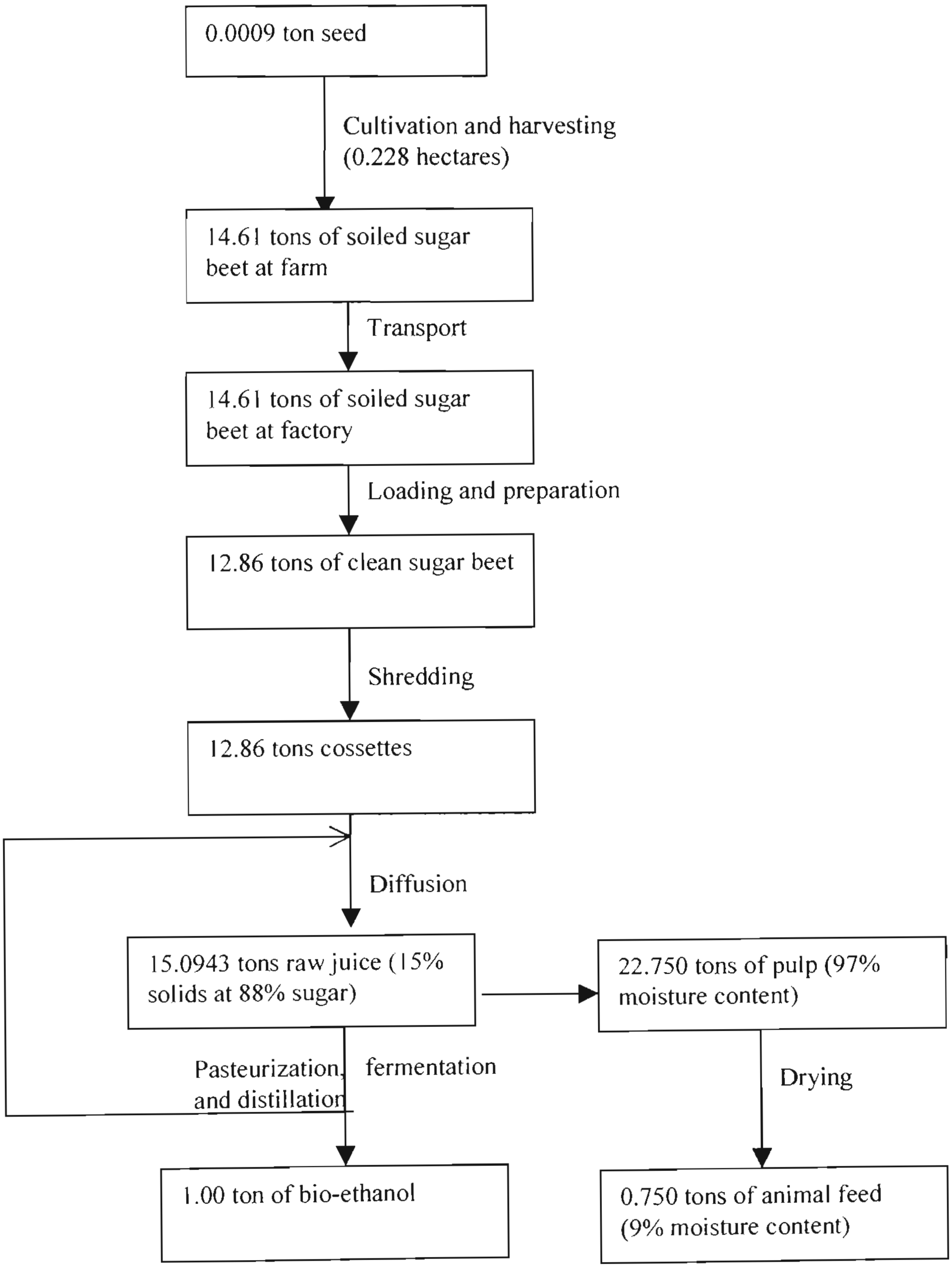


Figure 3.7: Processing of sugar beet to bio-ethanol.

Source: http://www.shu.ac.uk/rru/reports/scp21-3_appendix_q.pdf

Given the high cost of sugar cane, corn, and sugar beet feedstock that limit the economics of ethanol fuel development globally, developing alternative agricultural sources of ethanol fuel continues to draw increasing attention from researchers and developers around the globe. The high-energy efficiency of sweet sorghum has attracted major global attention (Mvududu *et al*, undated; Woods, 2001; Yamba, 2004). Tests performed by Mvududu *et al.* (undated) in southern Africa show ethanol yields of 3500 liters per ha per crop over a period of 3-4 months. The estimation has included possible losses resulting from harvesting, transportation and sorting of sweet sorghum feedstock. Internationally, ethanol yields exceeding 6000 liters per hectare per crop produced over a 3-4month period have been demonstrated (http://www.eeci.net/archive/biobase/B10191.html). The upper limit for sweet sorghum ethanol potentials is still not yet known, as recent findings suggest ethanol yields of 7000 liters/ hectare per crop (http://www.fao.org/ag/magazine/0202sp2.htm).

Further observations clearly demonstrate the energy efficiency of sweet sorghum extending beyond the bio-ethanol fuel industry (Table 3.2). Factors that improve the value of sweet sorghum as the source of energy include the low production costs of the crop when compared with all other crops currently used to produce ethanol fuel per unit time (see Section 3.4). Sweet sorghum performs exceptionally well with a supply of about 2/3 of water consumed by sugar cane (Mvududu *et al*, undated; Woods, 2001). Compared to one sugar cane crop produced over a twelve-month period, under minimal conditions within the optimum production range (i.e. conditions that would yield a minimal average of 3500 liters per ha given the potential yields falling above 6000 liters per hectare), sweet sorghum yields can double the energy value of sugar cane over the same period (Table 3.2). Based on the low production costs, energy efficiency, including the growing bio-markets, sweet sorghum in the near future will be a major source of ethanol fuel in the North, and the South as well.

Table 3.2: Sweet sorghum energy balance analysis.

Parameter	**Production (ton/ha)**	**Energy (Mcal/ha)**	**Energy (MJ/ha)**
1. Average sugar	12	48,000	200,928
2. Average bagasse production	19.5	68,250	285,695
Average energy production		116,250	486,622
	Production (liters/ha)	**Energy (Mcal/ha)**	**Energy (MJ/ha)**
Ethanol yield (2 kg/liter)	6,050	32,670	136,757
Energy consumed processing sugar to ethanol (can be provided by bagasse)		34,364	143,848
Total energy consumed using (a) sprinkler irrigation (b) surface irrigation		 9,487.1 5,353.1	 39,713 22,408
		Formula	**Average Energy balance**
Average energy balance for (a) sprinkler irrigation (b) surface irrigation		 32,670/9.487.1 32,670/5,353.1	 3.4 6.1

Source: http://www.eeci.net/archive/biobase/B10191.html.

3.3. Lignocellulose Ethanol Fuel

Ethanol fuel production potentials from lignocellulosic materials, besides the conversion efficiencies, can be dependent on the source and composition of lignocellulose. Sources of ethanol in lignocellulose are cellulose and hemicellulose. The percentage compositions of these sources and the potential ethanol yields vary from one feedstock type to another as suggested by various studies (Fig. 3.8) (Tables 3.3 and 3.4).

Table 3.3: Characteristics of lignocellulosic materials.

Biomass feedstock type	**Cellulose %**	**Hemicellulose %**	**Lignin**	**Sugars**	**Others**
Corn stover[1]	41	21	17	-	
Corn cobs[1]	45	35	15		
Sweet sorghum[3]	**36**	**16**	**10**	34	3
Sugar cane bagasse[2]	32-48	19-24	23-32	3	
Sugar cane leaves [3]	36	21	16	-	27
Hardwood[2]	45				
Softwood[2]	42				
Switchgrass[1]	45	31	12		
Bamboo[2]	41-49				
Newspaper[3]	62	16	21	-	1
Municipal solid waste[3]	33	9	17	-	41

Sources: [1]Mani *et al.*, 2002; [2]Scurlock, undated; [3]Shleser, 1994.

Table 3.4: Theoretical ethanol potentials in gallons per dry ton of feedstock.

Feedstock	[1]Ethanol potentials (gallons/dry ton
Corn	124.4
Corn stover	113.0
Rice straw	109.9
Cotton gin trash	56.8
Forest thinnings	81.5
Hardwood sawdust	100.8
Bagasse	111.5
Mixed paper	116.2

Source: U.S.DOE, 2002.

Table 3.5: Possible conversion efficiencies for sucrose, cellulose, and hemicellulose to ethanol.

Feedstock	Low end of range	High end of range	Average used in calculations
Sucrose to glucose & fructose	99%	100%	99.5%
Cellulose to glucose	95%	100%	97.5%
Hemicellulose to xylose	50%	90%	70.0%
Glucose to ethanol	95%	100%	97.5%
Fructose to ethanol	95%	100%	97.5%
Xylose to ethanol	40%	90%	65.0%
Sucrose to ethanol	94%	100%	97.0%
Cellulose to ethanol	90%	100%	95.1%
Hemicellulose to ethanol	20%	81%	50.5%

Source: Shleser, 1994.

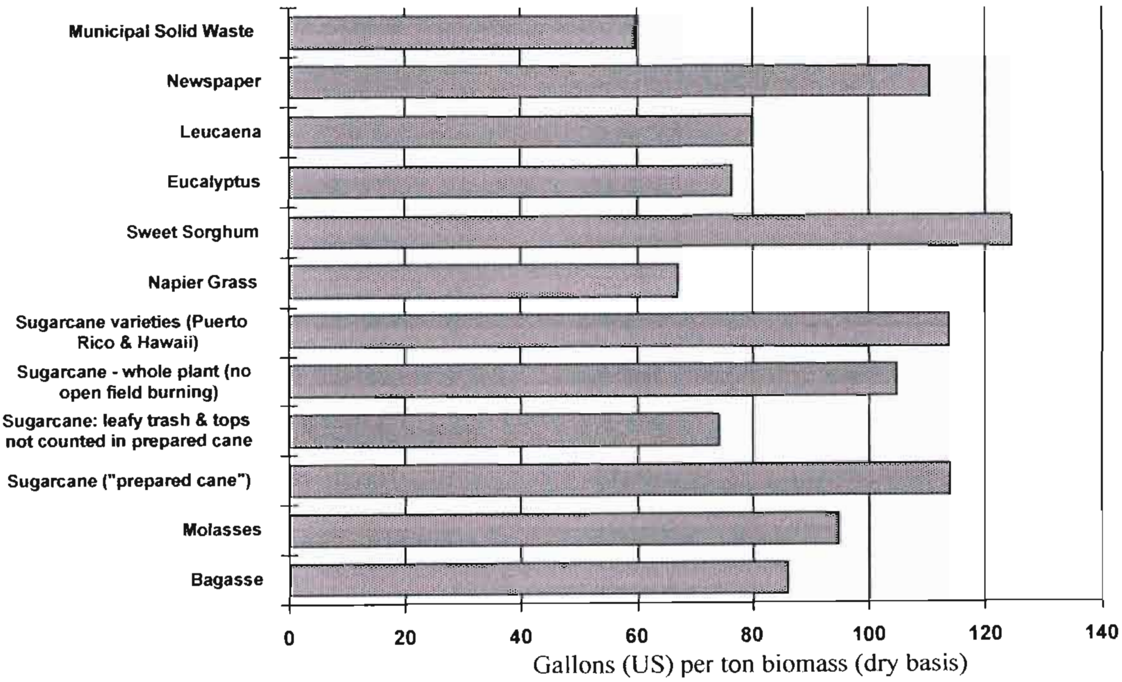


Figure 3.8: Potential yields of ethanol from lignocellulosic bone dry biomass.

Source: Shleser, 1994.

Hettenhaus (1998), Shleser (1994) and others have discussed in greater details the conversion process of lignocellulose to ethanol. Further discussion of the process is not necessary in this work. However highlighting the diverse implications of converting sugar, starch, as well as lignocellulose is relevant to this work, which is undertaken in the next section.

3.4. Implications of Bio-Ethanol Fuel Development

While the importance of agricultural crops as dedicated feedstocks for industrial applications extends beyond the economy of the transport industry, the focus in this section is on the production of ethanol fuel using agricultural crops. The focus on bio-ethanol fuel is stimulated by the sensitive tradeoffs associated with successful development of the industry, besides those that are economically oriented.

Replacing conventional fuels with ethanol fuel requires increased conversion of biomass materials into ethanol. In order for global bio-ethanol fuel to replace an important percentage of gasoline (i.e. significantly expand beyond the 40% of the fuel-demand level per year), extensive production of agricultural crops would need to be achieved to serve the fuel industry alone (Smith *et al.*, 2004). Shapouri *et al.* (2002) calculations show that using ethanol fuel increases atmospheric pollution. Shapouri *et al.*'s assertion has been based on the observation that ethanol's energy ratio as a fuel is 1.34. This means that for each 100 units of ethanol emissions coming out of the tail pipe, a further 75 units are burnt somewhere (Ferguson, 2003). Assessing environmental implications of bio-ethanol fuel combustions on the basis of tailpipe emissions can be extremely limited.

Replacing imported gasoline with ethanol certainly holds major local economic benefits. However, realising these benefits demands that more land becomes available for feedstock production. Ferguson (2003) created the impression that biomass cannot successfully replace a significant fraction of the world's gasoline currently consumed in the transport industry. Supporting this claim, Ferguson demonstrated that replacing 19% of the U.S.A. gasoline consumption of 480 billion liters per year (March 2000 data) would require 50 million hectares to produce corn. This assumes that 3108 liters are produced per hectare using corn starch, excluding the production of ethanol fuel from lignocellulosic materials such as corn stover. Converting corn stover to ethanol fuel would mean that more synthetic fertilizers have to be manufactured to improve soil nutrients on one hand. Using ethanol to manufacture synthetic fertilizers would automatically increase the consumption pressure on land systems on the other hand. Eventually, the benefits of using bio-ethanol fuel, because of the presumed environmental benefits would become significantly compromised.

The economic implications of bio-ethanol ethanol fuel development are well documented (see Aden *et al.*, 2002; McAloon *et al.*, 2000; Whims, 2002).

3.5. Summary and Conclusion

The discussion given in this chapter has shown the global use of different agricultural crops (e.g. corn, sweet sorghum, sugar cane and grain sorghum) to produce ethanol fuel. Advantages and limitations of these crops for ethanol fuel production have been briefly discussed. Highlighted in the discussion is that the choice of bio-ethanol feedstock is largely determined by a series of conflicting parameters. Optimizing the industrial use of agricultural crop resources can significantly reduce the negative economic implications of bio-ethanol fuel development. With the exception of environmental limitations resulting from a developing human population, most of the limitations associated with bio-ethanol fuel development can be effectively minimized over time. Achieving this process however requires greater understanding of the bio-ethanol fuel industry in relation to environmental limitations and the infinite upper limit of human development. This process requires intensive research and development of the product, which can only be achieved though making major tradeoffs for long-term gains. Competitive human development per capita among the rich, as well as the degrading hunger and survival activities of the poor are the most important challenges facing humanity in this era where global energy deficiency and supply uncertainties are excessively high.

The next chapter describes the methodology used to test the hypotheses of this study.

Chapter Four

Methodology and Data Analyses

4.0 Introduction

In previous chapters, attention has been drawn to the limitations of current approaches used in assessing potentials for bio-ethanol development all over the world. Hence, the total viability of the bio-ethanol fuel industry around the globe is largely dependent on greater support from governments through guaranteed price structures, market creation, subsidies and incentives. The degree to which these parameters determine the success of bio-ethanol fuel limits the long-tem capability of the industry to outperform competing products in its line in non-regulated market environments. The recent declines in sales of ethanol fuel observed in Brazil can be used to identify the negative impacts of non-sustainable government supporting systems (see Moreira, 2000, Moreira and Goldemberg, 1999). As a result, government-supporting mechanisms (e.g. promotional policies) observed elsewhere in the world, or suggested by myopic developers, are neither considered in this analysis nor do they deserve to be considered as prerequisites in planning the long-term development of bio-ethanol fuel in future. The world must promote the rationality of competitive product research, demand creation and business success in developing indispensable resources such as renewable energy. Evidently, the irrational principles of sustainability by which bio-ethanol fuel is promoted impair the outmost performance of rational earth science (see Chapter Eight).

Based on the argument given above, the assessment of lignocellulosic bio-ethanol potentials in southern Africa as presented in this chapter follow an integrated approach (self-regulating process) that has not been used elsewhere in the world. Technological materials developed by workers such as Elander (2002), Hettenhaus (1998), Mani *et al.* (2002), Shleser (1994), U.S.DOE (2001) form the bases of the methodology conceived for this investigation. Aden *et al.*, (2002), Kerstetter and Lyons (2001), McAloon *et al.* (2000) and many others have comprehensively illustrated the economics of producing ethanol fuel from lignocellulosic materials in the U.S.A. Describing the conversion process of lignocellulose to ethanol fuel is best relevant elsewhere than in this work. Further, possible strategies toward reducing the cost of lignocellulose conversion to ethanol fuel have been presented in greater details by Ashworth (undated) and McMillan (2002a; 2002b). In overall, this chapter describes the procedure toward exploiting sugar cane lignocellulose for producing ethanol fuel.

The methodological approach developed for this work has been designed to effectively demonstrate:

(a) that statistical departures of lignocellulosic bio-ethanol potentials influence the total viability of the bio-ethanol industry more than the statistical mean averages, a process which has not been considered anywhere in the world prior to this study,

(b) that lignocellulosic ethanol production offers improved investment opportunities for the agricultural industry over the subcontinent, when compared with sugar, and finally

(c) that organic sources of bio-ethanol fuel have much, but different, environmental problems and production limitations as fossil fuels.

4.1 Methodology Overview

Different processes and parameters have been rationally integrated in the methodology used for this investigation. Processes include the (a) annual supply of sugar cane to 18 sugar cane mills, (b) availability of lignocellulose per sugar mill catchment, and (c) annual variability of lignocellulosic ethanol potentials. Parameters comprise of (a) gasoline volume sales in the region, (b) feedstock and land stock potentials for ethanol production, as well as (c) human population. A procedure has been developed to ascertain the impact of human consumption of bio-ethanol fuel per capita on land stock potentials. Combining these differential factors early in the analysis has necessitated the use of an integrated methodological approach for data processing and analyses to test the hypotheses of this work. Before detailing this approach, defining southern Africa as used in this study is a priority undertaking.

Whereas 75% of the sugar cane producing countries in the SADC region has not been considered, the remaining 25% of countries in this region account for more than half of the cane produced by SADC as a whole. In turn, this 25% of countries accounts for all sugar cane produced by the Southern African Customs Union (SACU) here considered as the southern African region. On the basis of this observation and others given in Chapter 1, it suffices to use the 25% of countries responsible for the sugar cane produced by SACU to represent the southern African region as used throughout the presentation of this work. These countries that define southern Africa therefore are Swaziland and South Africa

Further, in some of the SADC sugar cane producing countries (e.g. Tanzania and Mozambique), the sugar industries have undergone rehabilitation programmes over the last few years. Including these countries in the total analyses, on one hand, would largely compromise the quality of the findings. While their exclusion, on the other hand, has improved the local scale understanding of bio-ethanol variability without compromising the application of the lignocellulose bio-ethanol development model in all SADC sugar cane producing countries. The tremendous influence that Illovo Sugar Company, South African Sugar Milling Research Institute and the South Africa Sugar Experiment Station (SASEX) have on the sugar cane industry development in the SADC region perfectly links the findings of this study within the SACU countries to the rest of the SADC sugar cane producing countries.

4.2 Sugar Cane Belt

Sugar cane production in southern Africa occurs along the eastern lowlands, forming a sugar cane belt from the Eastern Cape through Kwa-Zulu Natal, Swaziland to Mpumalanga (Figs.4.1- 4.2) (Table 4.1).

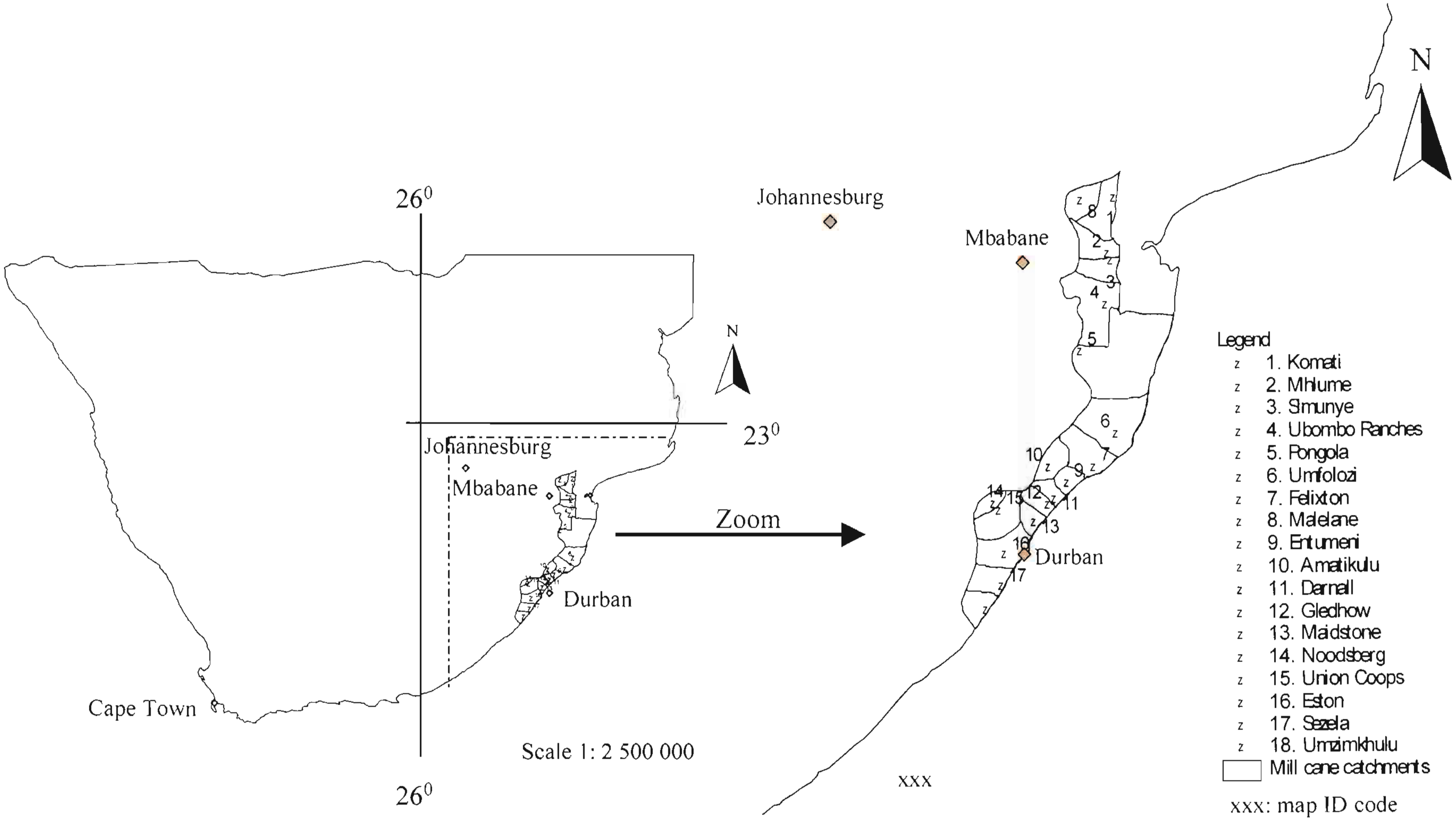


Figure 4.1: The sugar cane belt of the region.

Table 4.1: Spatial location of sugar mills along the eastern cane belt.

ID	Sugar mill	Country	Sub-regional grouping
1	Komati	South Africa	Northern mills
2	Mhlume	South Africa	
3	Simunye	Swaziland	
4	Ubombo Ranches	Swaziland	North central mills
5	Pongola	Swaziland	
6	Umfolozi	South Africa	
7	Felixton	South Africa	Central mills
8	Malelane	South Africa	
9	Entumeni	South Africa	
10	Amatikhulu	South Africa	
11	Darnall	South Africa	South central mills
12	Gledhow	South Africa	
13	Maidstone	South Africa	
14	Noodsberg	South Africa	
15	Union Coops	South Africa	Southern mills
16	Eston	South Africa	
17	Sezela	South Africa	
18	Umzimkhulu	South Africa	

4.3 Methodological Approach

The methodology adopted for this work has the following major activities:

(a) quantifying and assessing the spatial variability of bio-ethanol potentials on the basis of feedstock supplies across the region,

(b) characterizing bio-ethanol departures from the statistical normal means,

(c) evaluation of sugar cane mills to locate potential plant sites, as well as in economic and market assessment,

(d) observing the annual changes of bio-ethanol potentials per unit area at the local scale,

(e) demonstrating the implications of intensive bio-ethanol fuel consumption per capita for land stock potentials on a local scale (Swaziland), and finally

(f) understanding the principles defining sustainability and whether these principles are relevant to the development of the bio-ethanol fuel industry in all parts of the world.

4.4 Data Characterization

Grouping data into four separate entities has been given priority, as the process determines the efficiency of the integrated methodological approach. These data entities are: (a) cane feedstock, (b) gasoline consumption, (c) mill catchment area, and (d) human population.

4.4.1 Feedstock data

Historical records of sugar cane crushed in all 18 mills for the period 1991-2002 have been used (Appendix 1). These historical records were supplied by the Sugar Mill Research Institute, sugar mills, South African Sugar Association and the Swaziland Sugar Association. Detailed and more reliable data for all 18 mills covering a much longer period was not available.

At the local scale, historical records of cane production for the 1964-2002 period were used to explain the implications of increased bio-ethanol fuel consumption per capita for land stock potentials in a growing and developing population (Appendix 2). The Swaziland Sugar Association and the relevant mills supplied the data for this analysis.

4.4.2. Petrol data

Petrol data showing both spatial and temporal variability have been used to evaluate the potential market for bio-ethanol fuel. Periods covered by the historical records used for this product varied per country (i.e. data covered the 1996-2002 and 1994 – 2002 for Swaziland and South Africa, respectively) (Appendix 3).

Only historical records of petrol showing the annual consumption of 97-octane, 95-octane (unleaded), 93-octane and 91-octane (unleaded) have been used in the analysis.

4.4.3. Human population data

Investigating the impact of human numbers on land stock potentials and the production of bio-ethanol feedstock has only been undertaken at the local scale, represented by Swaziland. Human population data of the country for the years 1964-2002 was used in this analysis (Appendix 4). The Swaziland Central Statistics supplied annual human population data. Human population data gathered from other sources is fully referenced in the report.

4.4.4. Bio-diesel and bio-ethanol potentials

Bio-diesel and bio-ethanol potentials from sources other than lignocellulose have been obtained from dependable sources (Appendix 5). Full references of these sources are given in this report.

4.5 Method of Data Analyses

Data analyses focused on three separate processes for the southern African region. These are:

(a) annual variability of feedstock production potentials,
(b) evaluation and siting of bio-ethanol plants, and
(c) bio-ethanol demand analysis and selling strategies.

4.6 Local Data Analyses

Using data supplies by Mhlume and Ubombo Ranches mills for the period from 1964-2002, the implications of feedstock production for land stock abilities per hectare of cane area have been investigated in Swaziland (Fig.4.2). Data analyses at the local scale focused on three separate processes per unit area of cane (i.e. bio-ethanol potentials per hectare of cane area). These processes are:

(a) annual variability of feedstock production potentials,
(b) variability of annual consumption pressure, and
(c) relationship between the annual mill cane catchment area and variability of the consumption trajectories (i.e. annual changes in bio-ethanol potentials and human population numbers).

Figure 4.2: Data sampling points in Swaziland.

4.7 Data Sorting

4.7.1 Consideration of cane properties for data sorting

Assessing the viability of cane as a renewable source of feedstock materials for bio-ethanol production has focused on trash (cane tops and leaves), as well as bagasse. The idea of working with databases of these two lignocellulosic feedstock materials was to separately understand the suitability of each feedstock type for bio-ethanol production. Further, this process would offer a better understanding of the economics of scale in fermenting lignocellulosic materials to bio-ethanol fuel.

Lignocellulose consisting of cellulose, hemicellulose and lignin is the principal component of the plant cell besides water. Of these three cell wall components, cellulose and hemicellulose, through a series of biochemical processes, can be converted to fermentable sugars. The break down (saccharification) of cellulose through biochemical reactions yields six-carbon sugars (hexoses), while hemicellulose mainly yields the five-carbon sugars (pentoses). The products of cellulose and hemicellulose of interest in the production of bio-ethanol are the six-carbon sugar glucose and the five-carbon sugar xylose, respectively.

Observations have suggested that different factors influence the percentage composition of cellulose and hemicellulose in cane and the feedstock types (e.g. cane variety and climate). For bagasse, the average percentage compositions of cellulose and hemicellulose used in this study were 39 and 27, whereas trash average compositions used were 36% and 21%, respectively (http://www.ott.doe.gov/biofuels; Shleser, 1994).

4.7.2 Characterizing annual events

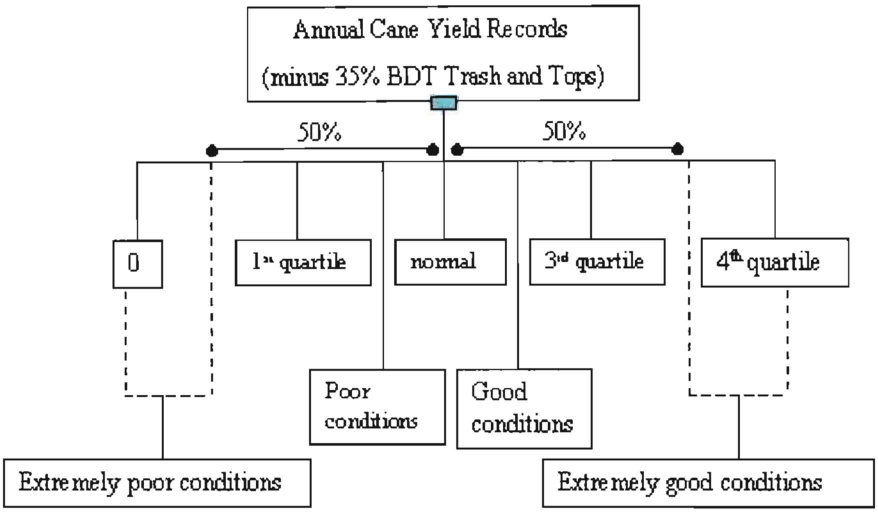
Sorting data to characterize annual events of all analysed processes followed the approach given in Section 4.4. Therefore, providing a priori definitions of the descriptive terms used in the analyses is important at this point.

Statistical quartiles have been used to sort sugar cane data and develop definitions of all annual events for processes analysed, with the exception of cane area and human population (Fig.4.3). In the latter case, no extreme annual cases could be convincingly defined by using statistical quartiles. Conditions above normal years refer to annual events falling above the statistical annual mean, while the opposite has defined those conditions failing to reach the annual statistical normal mean of all records analyzed (Fig.4.4). Extremely good (high) cane events refer to annual conditions falling above the 3rd quartile (i.e. annual events which have been at least 25% above the normal mean), whereas the opposite has defined extremely poor (low) annual events. Data was next sorted on the basis of cellulose and hemicellulose potentials, as bio-ethanol feedstock materials (Fig.4.5). Sorting data by conditions of glucose and xylose defined the annual events of bio-ethanol potentials.

4.8 Carbon Dioxide Variability

Although carbon dioxide gas is known for its greenhouse gas properties and the possibility of contributing to global climate change, the association of the gas with these processes has been ignored in the study. The assumption has been that all the carbon dioxide released during lignocellulose fermentation came from the atmosphere, and therefore becomes a recycled material. Characterizing conditions of carbon dioxide in this study has been done to demonstrate the potential resource for co-business development in the bio-ethanol industry. Carbon dioxide yields are expressed in tons, while ethanol yields are expressed in gallons. This difference in units between carbon dioxide and ethanol yields is observed where carbon dioxide yields fail to show greater increases (decreases) during above (below), as well as significant changes in extreme annual events. The irrelevance of carbon dioxide for this work has led to the use of tons instead of using smaller units, such as kilograms (or gallons). Should the interest of using smaller units arise in future, the carbon dioxide and ethanol yield ratio of 49:51% can be used to obtain reflective estimates of carbon dioxide production (or by simply converting tons into kilograms (see Section 4.13)).

(a)



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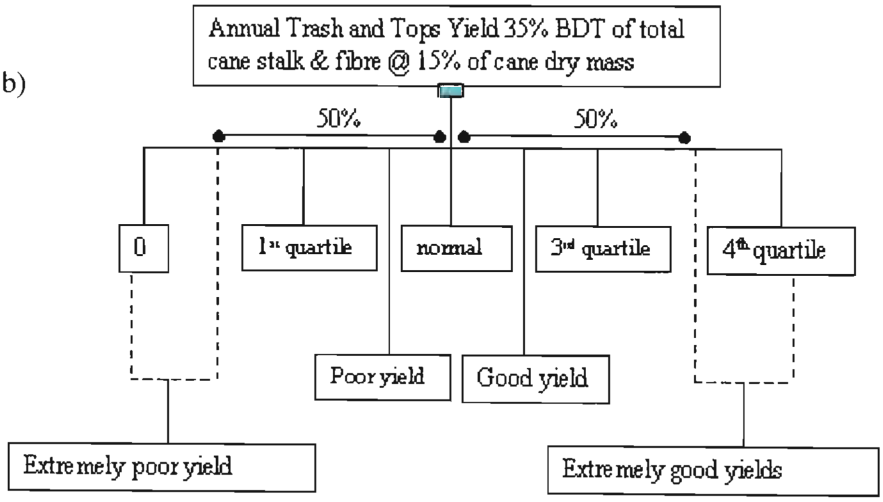

Figure 4.3: Classification of annual events (a) cane, (b) leaves and tops feedstock.

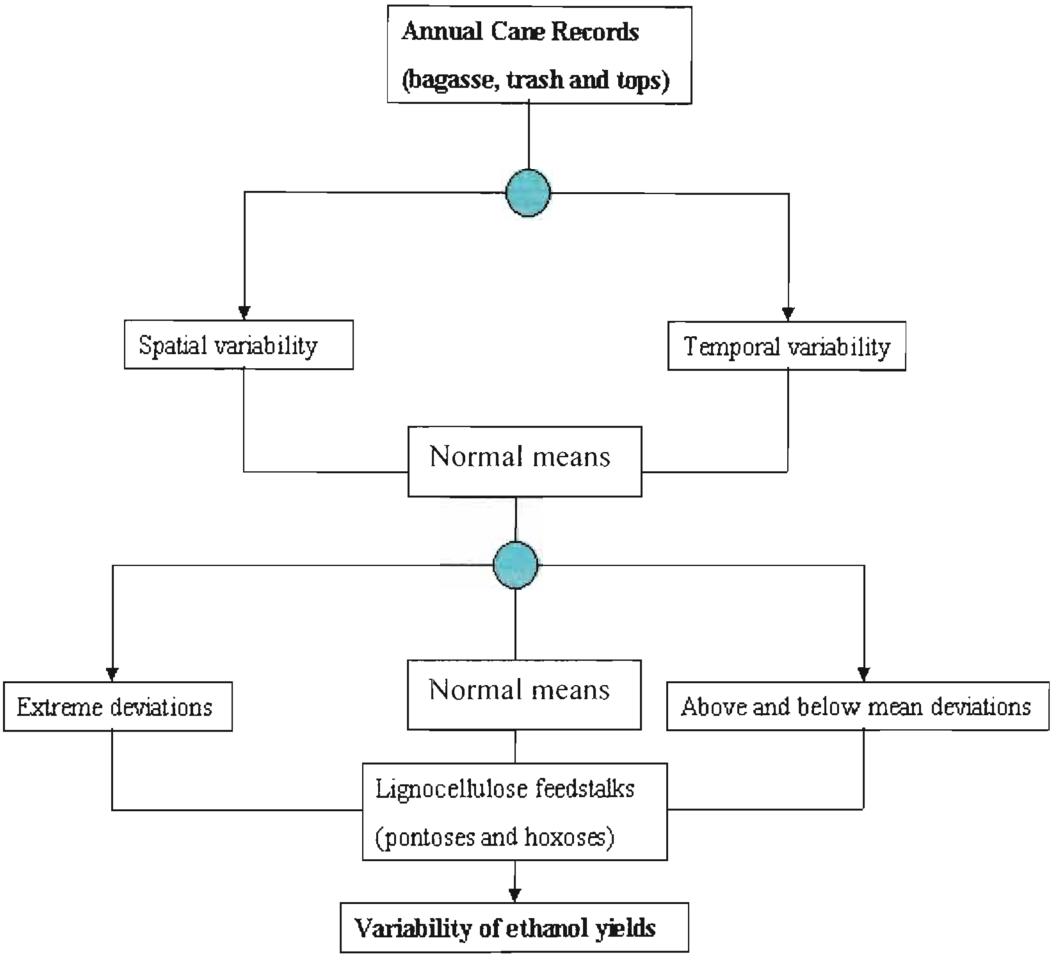

Figure 4.4: Ethanol feedstock data sorting.

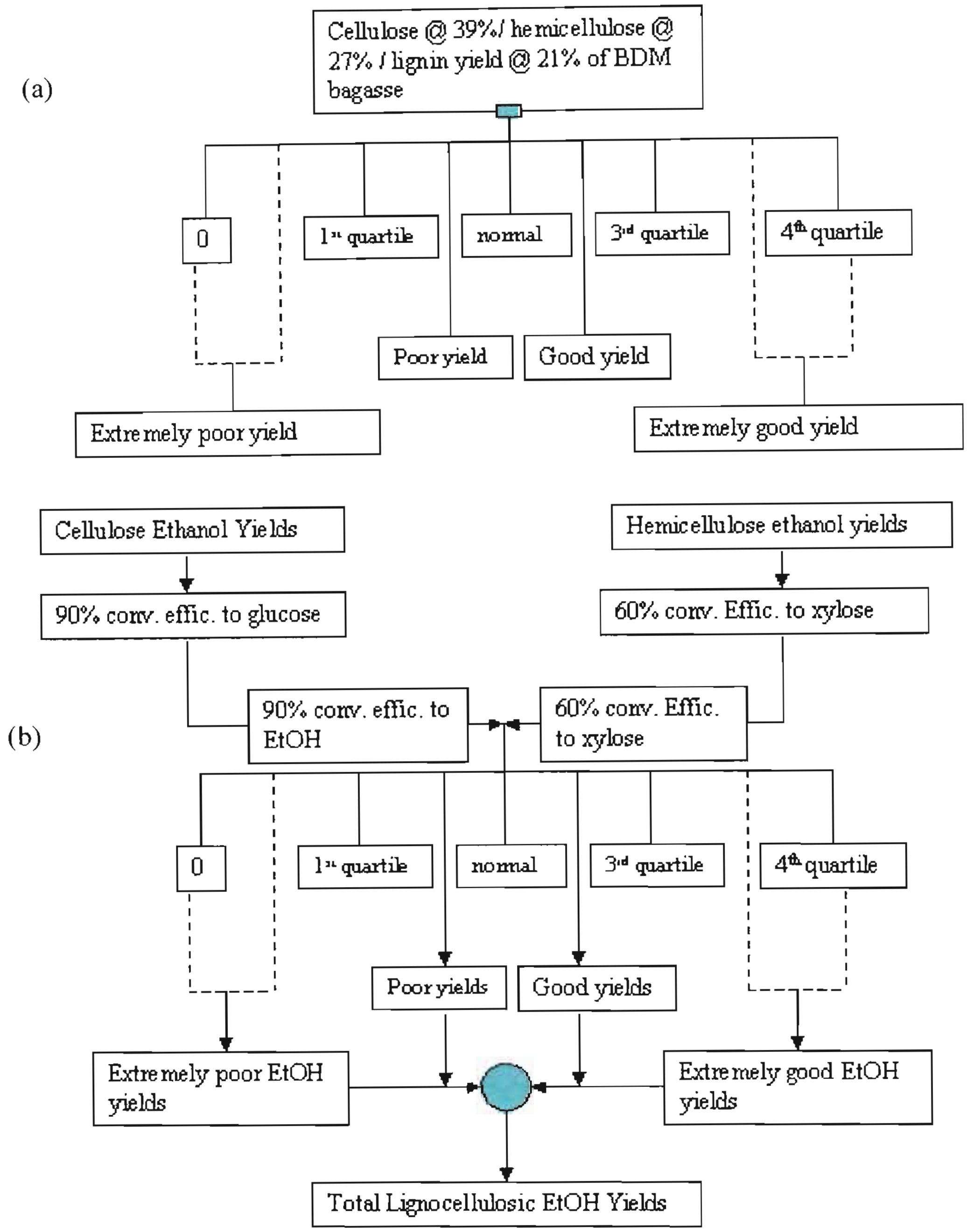

Figure 4.5: Data sorting and processing (a) lignocellulose, (b) ethanol production.

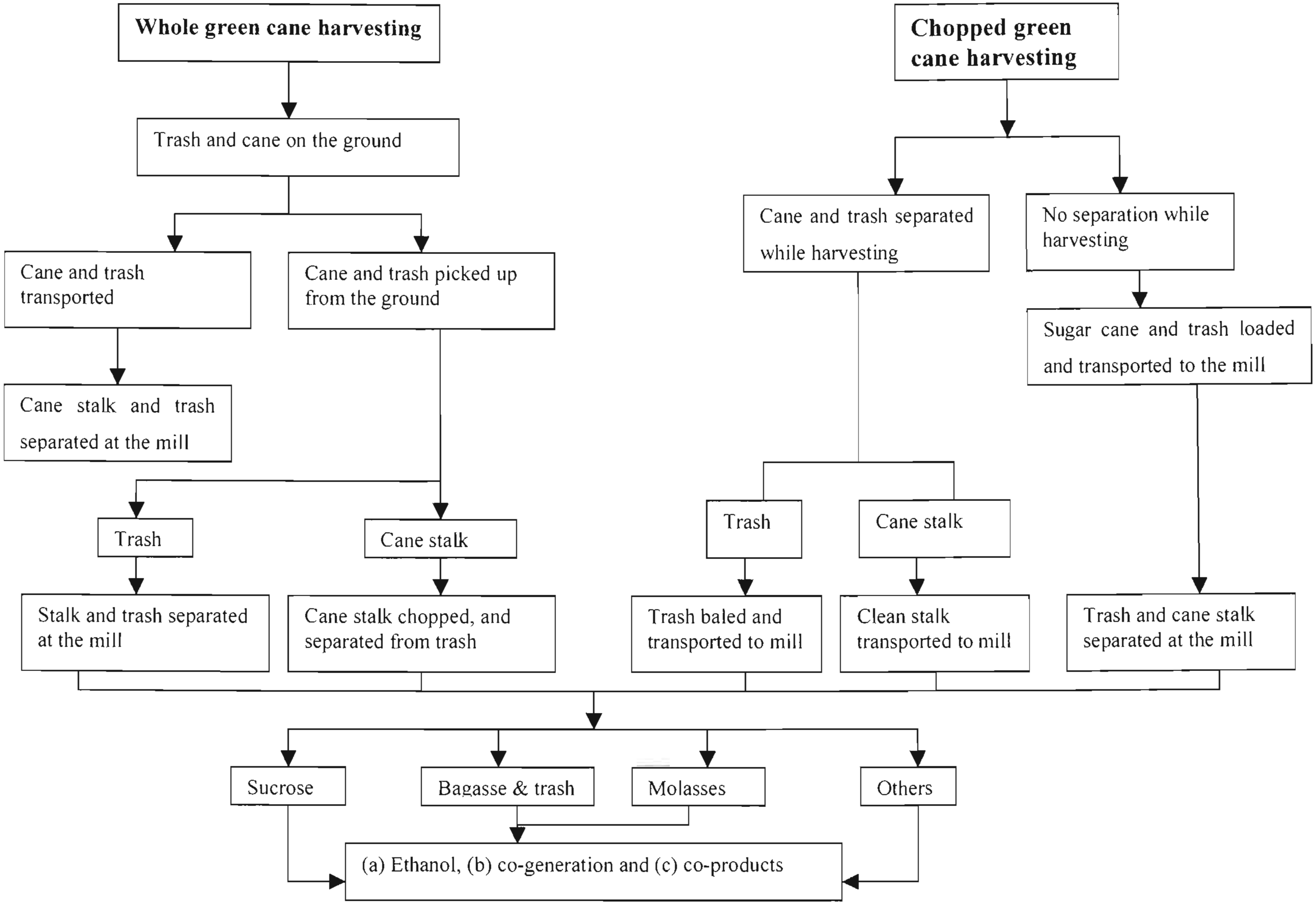

Figure 4.6: Possible routes to green cane harvesting for ethanol production. Adapted from Waldheim and Morris, 2000.

4.9 Gasoline

Petrol data sorting was first by quarters in a year (i.e. 4-month periods from the first month of the year), and then followed by years. Percentages of bio-ethanol fuel in gasoline considered to measure the market potentials are 10% (E10), 12%, (E12), 15% (E15) and 24% (E24).

4.10 Calculations Ethanol Potentials from Cane Cellulose and Hemicellulose

Kerstetter and Lyons (2001), McAloon *et al.* (2000) and others have described in detail specific technological approaches for fermenting lignocellulose to bio-ethanol. Each approach has been appropriately considered in this work as show below. Current biotechnological developments indicate that theoretically sugar cane fibers can yield 111.5 gallons (422 liters) of ethanol per bone dry ton (BDT) (U.S.DOE, 2002).

Shleser (1994) highlighted various conversion efficiencies of different lignocellulosic materials to ethanol (see Fig.4.11). These are as follows:

(a) cellulose to glucose conversion efficiency by mass (e.g. ton of raw material): low end of range = 95% and high end of range = 100%(Shleser, 1994); used conversion efficiency for calculations = 80%;

(b) hemicellulose to xylose conversion efficiency by mass: low end of range = 50% and high end of range = 90% (Shleser, 1994); used conversion efficiency for calculations = 60%;

(c) glucose to ethanol conversion efficiency by mass: 95% low end of range and 100% high end of range (Shleser, 1994): used conversion efficiency for calculations = 90%;

(d) xylose to ethanol conversion efficiency by mass: 40% of low end range and 90% of high end of range (Shleser, 1994): used conversion efficiency for calculations = 60%;

Although concentrated acid hydrolysis developed by Arkenol has been found to be more efficient, the dilute acid hydrolysis technology used by BCI has been considered here. The possibility of cost reduction in enzyme production and use for lignocellulose hydrolysis in the near future has favoured the choice of dilute acid hydrolysis for the work. Bacterial strains considered for co-fermentation of hexoses and pentoses are the recombinant strains of *Zymomonas mobilis*. Despite the very high current costs of hydrolytic enzymes, enzyme hydrolysis has formed part of the evaluation process. Bio-ethanol plant costs can be adjusted as costs of enzymes decline in future with new developments in biotechnology.

4.11 Approach to Economic Analyses

Given the nature of objectives and hypotheses of the study, no detailed analysis of ethanol economics has been given in this report. The magnitude of work required to develop a convincing analysis is surely beyond the scope of this investigation. Nonetheless, economic findings presented in this report have assisted in identifying sub-regions, which can develop economically viable bio-ethanol plants.

Various factors, as well as processes have been considered in formulating an effective procedure for economic analyses. These factors have been briefly discussed below, while their detailed discussions have been given in other reports (see Kerstetter and Lyons, 2001; Todar, 2001; Wooley *et al.*, 1999). Developing a model that describes biotechnical processes and economics of lignocellulose ethanol in the region has required a wider source of variables. The initial process has been to identify a set of activity flows (Fig.4.7). Developing the process flows for the work has been largely influenced by these variables and the parameterisation process of the ASPEN Plus5 model (Wooley and Putsche, 1996; Wooley *et al.*, 1999). Detailed work done by the U.S.DOE to assess the viability of lignocellulosic ethanol production in the U.S.A. provided the basis for technological assessment, process functionality and consideration. Kerstetter and Lyons (2001), McMillan (2002a; 2002b), McAloon *et al.* (2000) and others have given a detailed discussion of the work. The model used consists of unit operation blocks, streams and control blocks. The overall model is thermodynamically rigorous and uses built-in physical properties, as well as properties developed at the NREL6 (Wooley *et al.* 1999).

For the study, plant costs have been adjusted based on work done for the U.S.DOE, where materials were priced at the 1999 US$ (Kerstetter and Lyons, 2001). There have been no alterations made on the basis of technology where either corn stover or rice straw has been used as the feedstock, with the exception of feedstock costing, particularly bagasse. Bagasse has not been considered a waste product in the pricing process, but as a commercial product to farmers.

Costing of the technology, as well as the conversion process has been adapted from work proposed by U.S.NREL (Kerstetter and Lyons, 2001; Wooley *et al.*, 1999). While acknowledging that southern Africa lacks the appropriate technology and materials, it has been assumed that all materials would have to be imported and priced in the US$ rate. Costs used in this analysis only reflect the base case for which the equipment has been designed. Should the plant design change in future, the equipment would generally not be re-evaluated in detail. Using the following exponential scaling expression for a different sized plant, the costs can easily be determined by rescaling on the basis of the new size or some other characteristic changes related to the size of the plant (Equation 1) (Wooley *et al.*, 1999).

Equation 4.1:

$$\text{New Cost} = \text{Original Cost}\left(\frac{\text{New Size}}{\text{Original Size}}\right)$$

Costs of developing the byproducts have not been accounted for in the initial ethanol plant set up. Figure 4.8 demonstrates a simplified lignocellulose based bio-ethanol plant version, which is currently used by BCI International in the U.S.A.

4.12 Analysis of Land Stock Limitations

To address some of the limitations resulting from a broader set of data, analyzing parameters and processes threatening the viability of a bio-ethanol industry based on intensive agriculture has been undertaken at the local scale. The investigation has afforded an integration of different system flows characterizing the functions of the natural capital science comprising among others (a) natural resource limits, (b) economic laws, and (c) artificial capital. Mathematical models for computerized data manipulations have not been considered in the study, although such processes could help explain in detail the degree of association between the analyzed parameters. Nonetheless, their exclusion does not devalue in anyway the purpose and quality of the work presented henceforth.

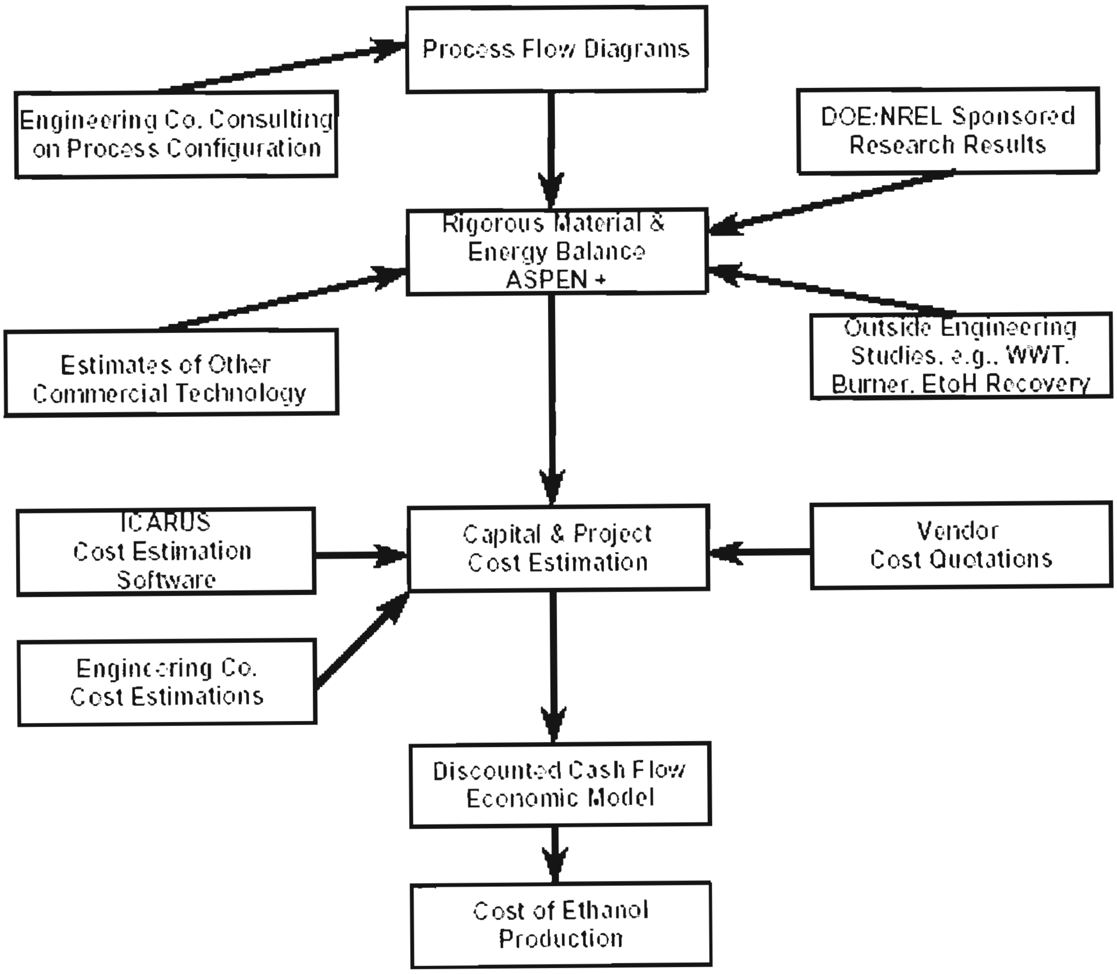

Figure 4.7: Activity flows in lignocellulosic ethanol technology evaluation.

Source: Wooley *et al.*, 1999.

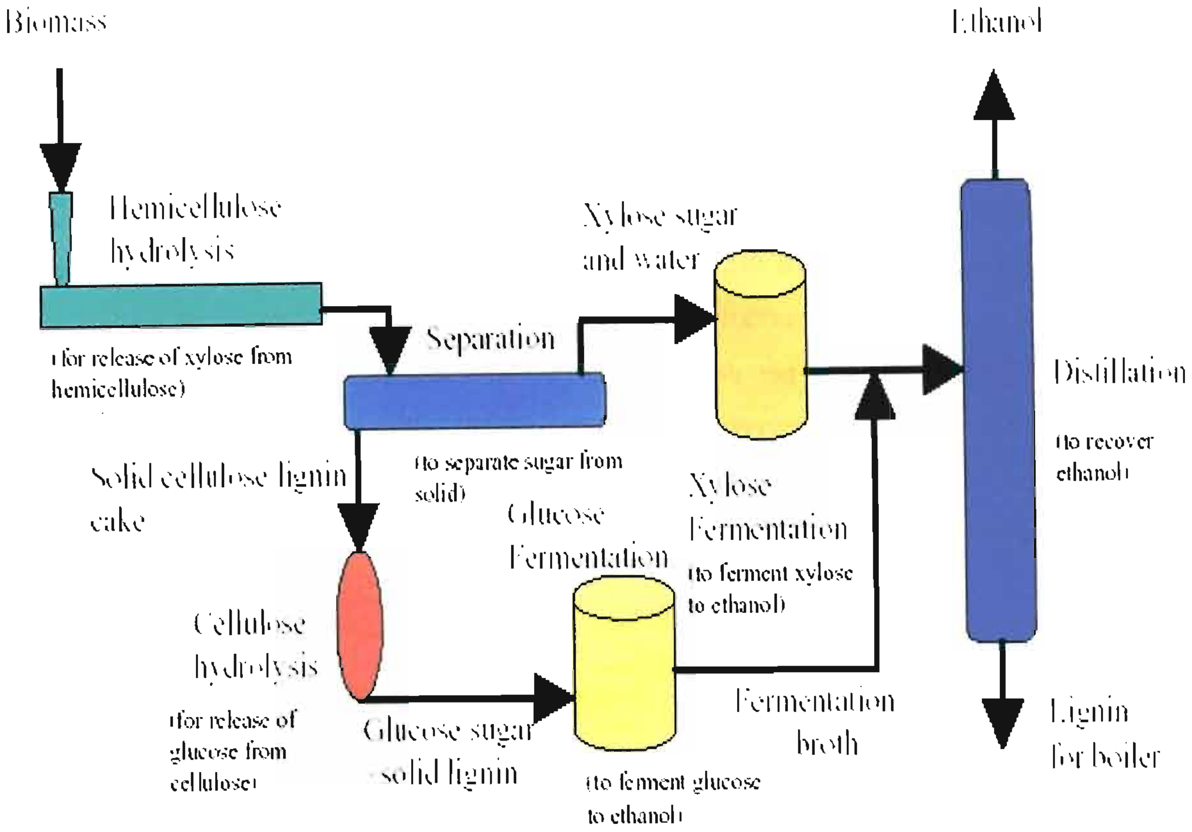

Figure 4.8: The simplified process for dilute sulphuric acid hydrolysis of lignocellulose and ethanol fermentation.

Source: BC International, Inc. http://www.bcintlcorp.com/

4.13. Physical Composites of Sugar Cane

Important sources of lignocellulosic ethanol fuel from sugar cane are bagasse, leaf tops and leaves (Fig.4.9). Annual yields of these parameters vary with cane varieties and under different physical conditions per crop variety. Clarifying or explaining the causes of the intra- and inter- annual variability of lignocellulose yields, as reflected by the differential ethanol fuel potentials (see Chapters Five and Six) and further highlighted in Chapter Eight, is beyond the scope of this study. Ripoli (1991) (cited in Ripoli *et al.*, 2000), Shleser (1994; 2002) and others have demonstrated the variability of the different sources of lignocellulose in cane. Ripoli *et al.* and Shleser have shown that the average moisture content of cane leaf tops is about 79.18mass% and 80-88mass% respectively (Fig. 4.9) (Table 4.2). Ripoli estimated the green leaf moisture at 70.02% by mass. The humidity of the dry cane leaves has been estimated at 12.94mass% and 18-30mass% by Ripoli and Shleser respectively. Shleser (1994) estimated the inclusive moisture content of cane leaf tops, dry lower leaves and green leaves at 50% of their 40mass% with respect to the total mass of cane stalk harvested. The analysis of bio-ethanol potentials using these resources considers the average 50mass% suggested by Shleser, which has been generally confirmed in separate investigations (see Ripoli, 1991, Ripoli *et al.*, 2000). The moisture content of these cane resources vary depending on the age of the crop and the environmental conditions during harvesting. Conservatively, the 35mass% of cane tops and leaves per cane unit mass harvested has been used to estimate the annual yields of these resources in the cane industry instead of the 40mass% suggested by Shleser (1994; 2002). Green cane harvesting is the method considered for harvesting leaf tops and leaves (Fig. 4.10).

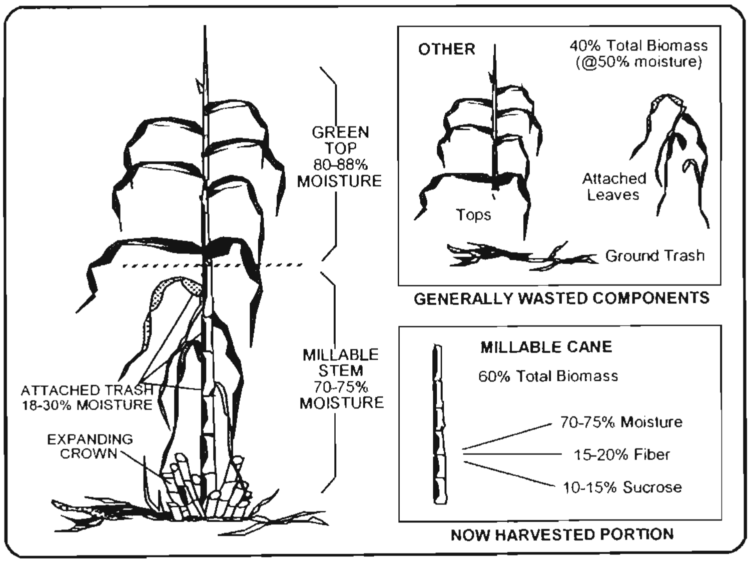

Figure 4.9: Sugar cane resources.

Source: Shleser, 1994; 2002.

Table 4.2: Moisture content in separate cane resources.

Cane lignocellulose sources	**Humidity (mass%)**
Stalks	81.67
Leaf tops	79.18
Green leaves	70.02
Dry leaves	12.94

Source: Ripoli, 1991 (cited in Ripoli *et al*, 2000).

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Save Our Planet Earth from Human Greed
For the Blessed Soul of a Born Child

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Dedicated to All
Children of the World for their Visions Rest Deeper than a Gold

(a)

(b)

Figure 4.10: Sugar cane (a) green harvesting (i.e. harvesting with no pre-burn) with high biomass (trash) yields, (b) pre-harvesting burn to eliminate most of the trash.

Source: Ripoli *et al*., 2000.

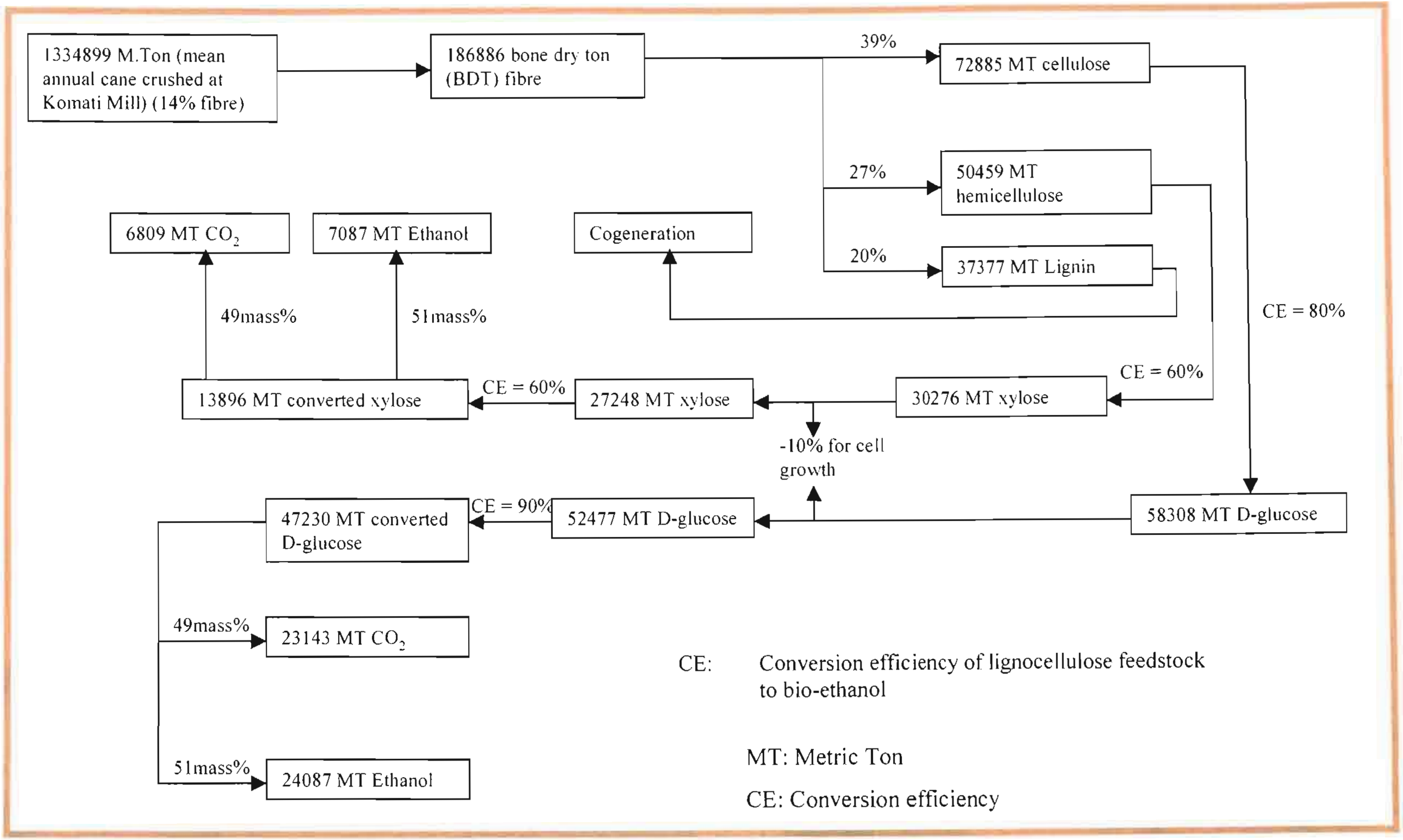


Figure 4.11: Estimation of bio-ethanol potentials from sugar cane (bagasse) fibre.

Note: The same process was used to estimate bio-ethanol potentials from sugar cane trash (leaves and tops) per given the various moisture contents (see text for the procedure) where the average percentage compositions of cellulose and hemicellulose used were 36% and 21% respectively.

The 14mass% average of fibrous material (mainly bagasse) at 50% humidity (moisture content) in crushed cane has been used to quantify bagasse yields. There is no single way of measuring the amount of cane trash (leaves (green and dry) and leaf tops) produced per unit area, because of the significant differences in moisture contents (see above discussion). Nevertheless, the simplified procedure developed by Shleser (1994; 2002) combining all these resources has been considered in this work. Based on these assertions, a specific procedure has been developed and used in determining the potential yields of bio-ethanol fuel (Fig. 4.11). From this percentage ratio, differences in ethanol fuel yields are expected from these two types of cane resources. Whereas lower ethanol potentials are expected for bagasse at 14mass% (50mass% humidity), the opposite may be the case for trash. The question is now to verify whether this assertion holds as per the findings given in the next two chapters.

The next chapter demonstrates the general variability of lignocellulosic bio-ethanol potentials over the subcontinent.

Chapter Five

Variability of Lignocellulosic Ethanol Potentials

5.0 Introduction

Demonstrated in previous chapters is the global application of ethanol as a transport fuel derived from agricultural crops. Differential sources of bio-ethanol fuel have been suggested in the process. Limitations of these dedicated sources of bio-ethanol fuel have been expressed. Nevertheless, using food crops as supplementary feedstock to cheaper lignocellulosic materials is crucial in the development of low cost biofuels worldwide. Hence, the urgent need to explore cheaper sources has been the subsequent indication in the previous chapter. Although neither of the feedstocks indicated in the previous chapters is currently used in southern Africa to produce ethanol fuel (i.e. countries within the southern African region as defined in this study), the abundance of bio-ethanol fuel feedstock in the region is a factor demanding serious consideration. More important to consider in this epoch is the need to identify the successes and weaknesses in exploiting the various feedstock types available over the subcontinent for ethanol fuel development. Identifying potential sources, as well as characterising spatial and temporal variability of these sources forms the basis for efficient bio-ethanol fuel development in the region. This chapter and the next are designed to serve this purpose where cane lignocellulose is the possible source of bio-ethanol fuel. Calculations of bioethanol potentials when cane fibre is used as a dedicated feedstock are based on the procedure described in Chapter Four (refer to Section 4.13, Fig.4.11)

Three conditions of bio-ethanol potentials expressed by the annual variability of cane production over the subcontinent define the structure of this chapter. These three conditions are:

(a) annual bio-ethanol potentials during normal mean years of feedstock production over the period (1991-2002) analysed,

(b) above (below) departures of annual bio-ethanol potentials from statistical normal means of cane production, and

(c) variability of bio-ethanol potentials during extremely high (low) years of cane production.

5.1 Bio-Ethanol Potentials During Normal Years

5.1.1 Bagasse

During normal conditions, southern Africa can expect an important spatial variation of bagasse cellulose yields (Fig.5.1a). In terms of ethanol and carbon dioxide yield potentials, this spatial variation becomes less pronounced over the subcontinent as products range only between 0 and 50KTY (Fig.5.1b, c). Generally, most areas along the sugarcane belt show rather low potentials (0-25KTY (0-32MLY)) for cellulosic ethanol production during normal years.

In normal years of bagasse production, conditions of hemicellulosic ethanol potentials decline to low levels (0-25KTY (0-32MLY)) in all areas of the sugar cane belt (Fig.5.2b). When compared with hemicellulose, cellulose demonstrates an important influence on the general variability of bagasse ethanol and carbon dioxide potentials in normal years.

5.1.2 Trash

Although not very significant, there are more areas in the region experiencing increases in trash cellulose yields than bagasse during normal years (Fig.5.3a). This spatial variability is also reflected in the production potentials of trash cellulosic ethanol, as these potentials exceed 25KTY (25-50KTY) (32-63MLY) in just over half of the subcontinent (Fig.5.3b). The production of carbon dioxide during normal years of trash yields closely follows the spatial pattern of ethanol potentials (Fig.5.3c).

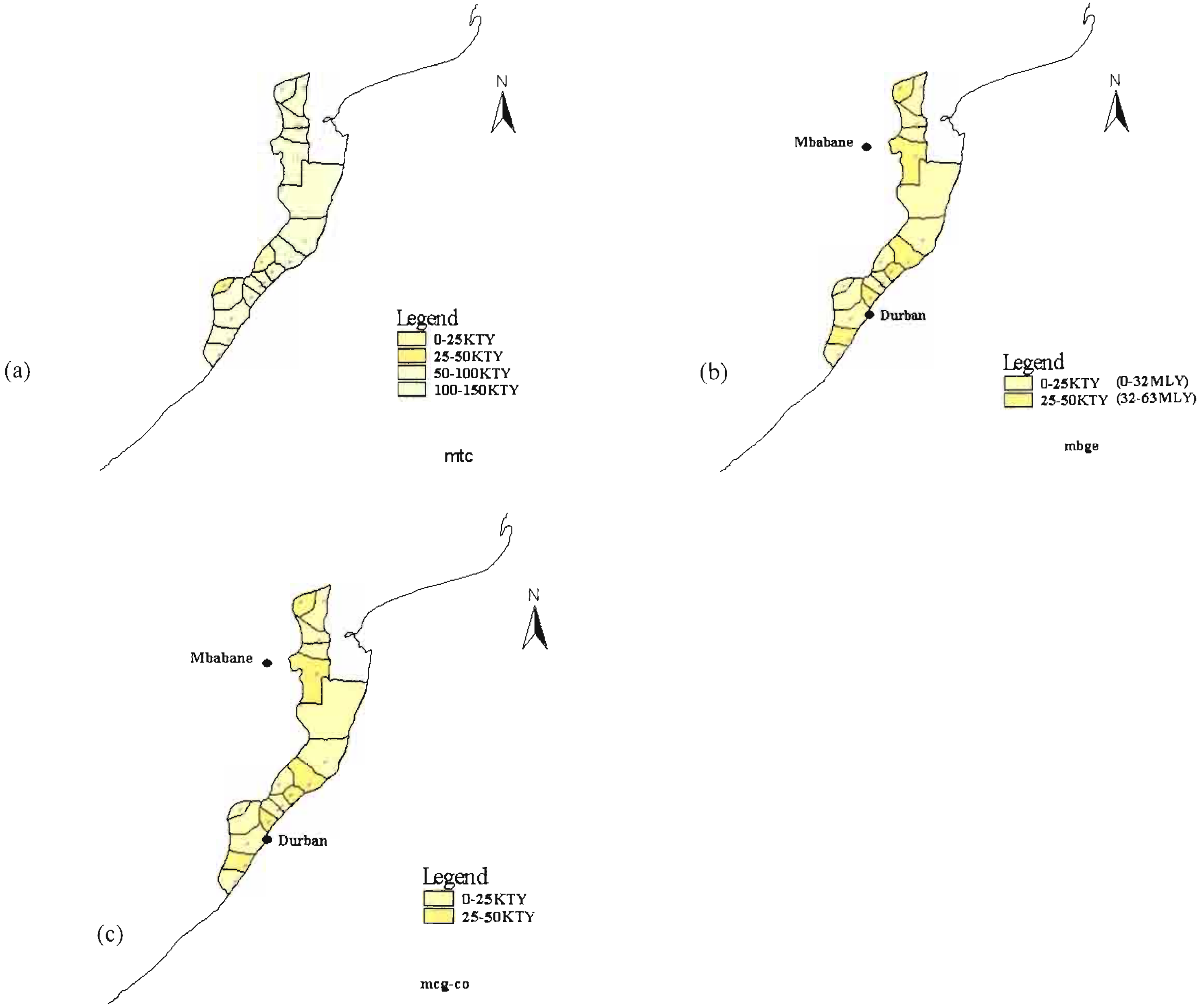


Figure 5.1: Mean annual conditions of bagasse (a) cellulose feedstock, (b) ethanol, (c) carbon dioxide.

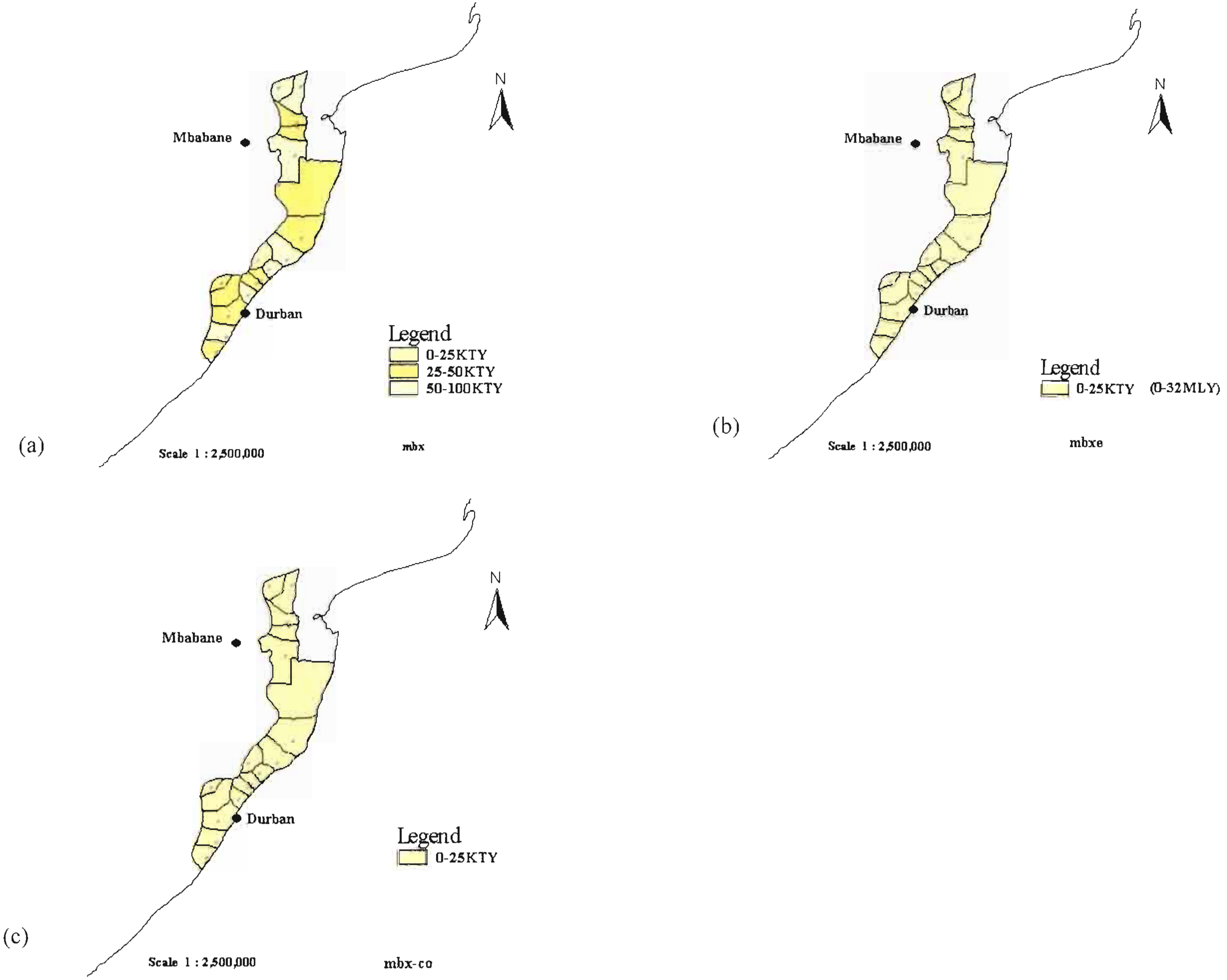


Figure 5.2: Conditions of mean annual bagasse (a) hemicellulose, (b) ethanol, (c) carbon dioxide.

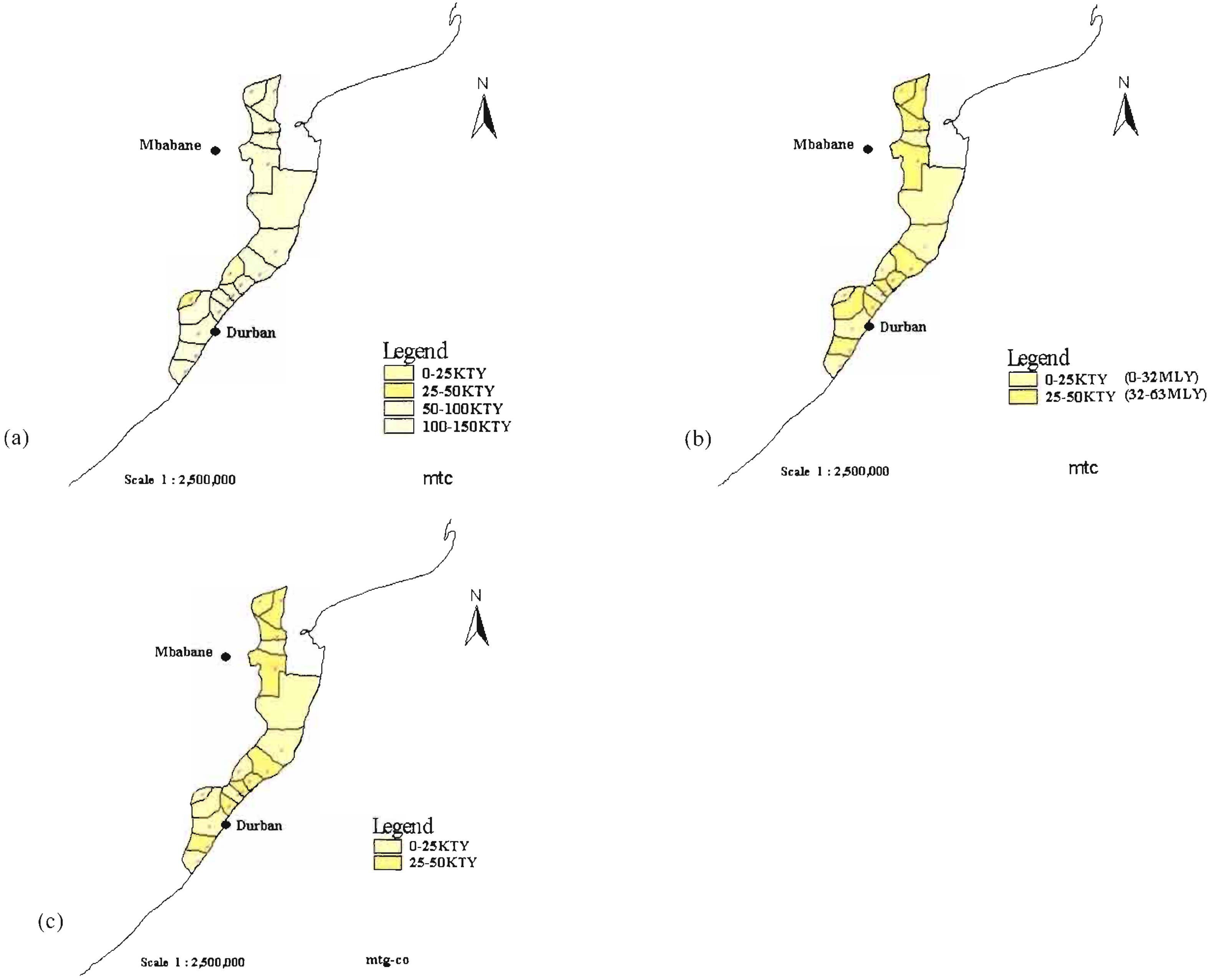


Figure 5.3: Mean annual trash (a) cellulose, (b) ethanol, (c) carbon dioxide.

There is an important relationship in hemicellulosic ethanol potentials when bagasse and trash are used as potentials feedstocks. In both cases, hemicellulosic ethanol potentials fail to exceed 25KTY (32MLY) (Figs.5.2b and 5.4b respectively).

Normal conditions of ethanol production provide an understanding of the processes, as well as changes in these processes that largely influence their (normal) development. While understanding the statistical annual normals of ethanol potentials affords the necessary planning baseline in developing the industry, on one hand, departures from normals, on the other hand, directly influence the economic viability of bio-ethanol development. Annual drifts of ethanol yields above normal years can be used characterize the processes necessary to create a long-term positive shift in annual-normal yields of ethanol, while the opposite applies for negative departures. Climate variability, land stock characteristics, cane agronomic routes, and the total management practices of the sugar cane crop are some of the crucial processes responsible for ethanol yield departures from normal conditions. Detailing the analyses of all the processes that lead to positive and negative drifts of ethanol potentials from annual mean conditions is beyond the scope of this study. However, Chapter Eight provides a comprehensive analysis of some of the processes, which can lead to inter-annual variability of lignocellulosic ethanol potentials. The findings presented in these chapters are conclusive as per process analyzed and therefore cannot be generally used to reflect other processes not investigated.

Departures of Ethanol Potentials from Statistical Norms

Positive annual departures of bio-ethanol potentials from normal annual means are given by the annual average cane conditions for the years with crushed cane falling above the statistical normal mean over the period analyzed. The opposite therefore defines annual conditions of bio-ethanol potentials below the statistical normal mean.

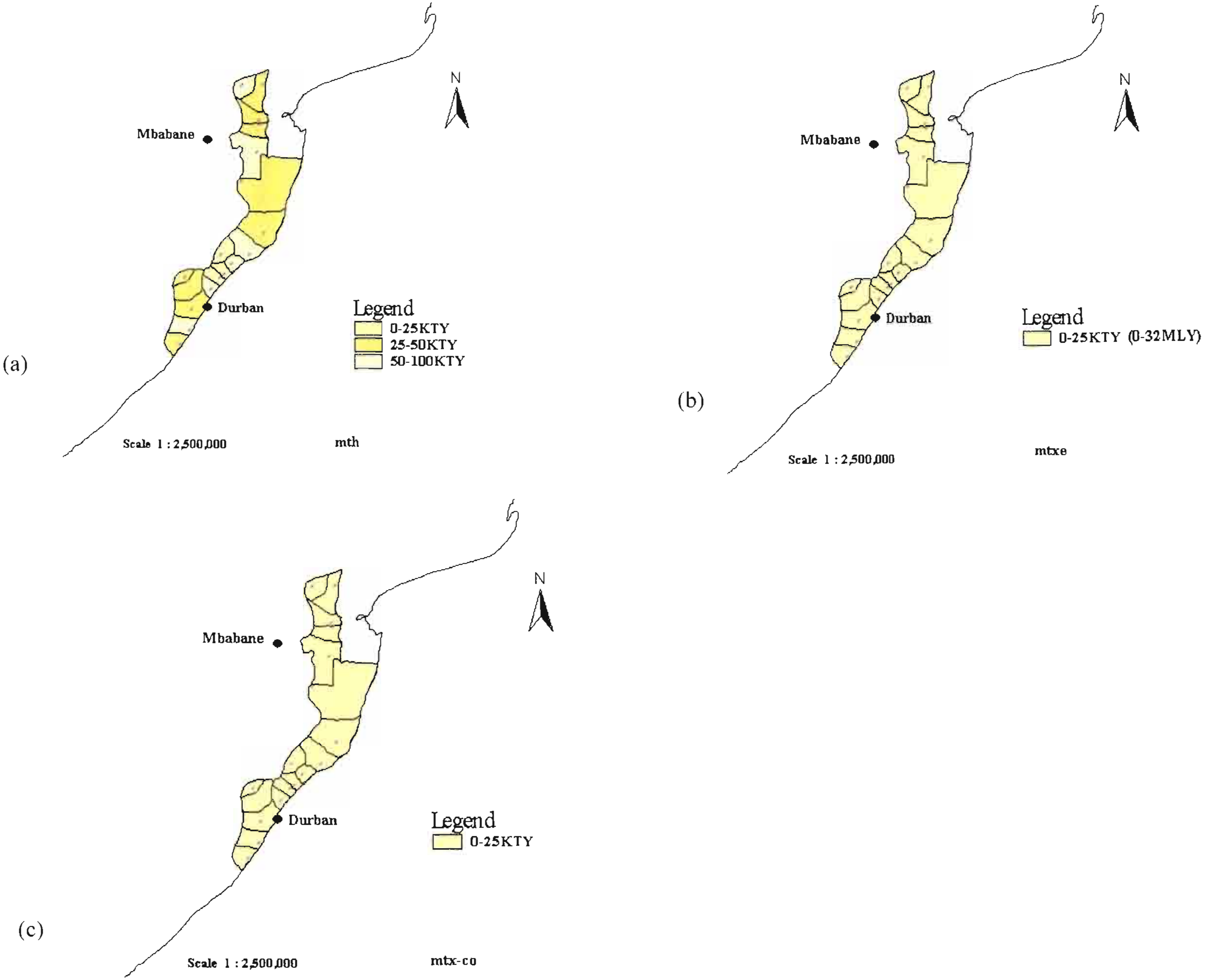


Figure 5.4: Mean annual trash (a) hemicellulose feedstock, (b) ethanol, (c) carbon dioxide.

5.2.1. Above normal mean conditions

5.2.1.1 Bagasse

Extrapolation of historical annual records of cane production suggests a very important phenomenon in above normal years. Increases in cellulose yields lead to higher ethanol production potentials in all areas of the subcontinent with minor exceptions (Fig.5.5). Over a reasonable portion of the region, annual ethanol potentials fall short of 25KTY (i.e. <32MLY), with most areas experiencing ethanol potentials ranging from 25 to 50KTY (32-63MLY) (Fig.5.5b). Carbon dioxide production shows the same potential (25-50KTY) in most areas of the region (Fig.5.5c). There is no improvement in (bagasse) hemicellulosic ethanol (carbon dioxide) production potentials from normal conditions, as annual yields in above normal years still remain below 25KTY in all areas of the sugarcane belt (Fig.5.6).

Given the above-highlighted departures of bagasse bio-ethanol in above-normal years, the question remaining unanswered is whether these conditions also hold where trash lignocellulose is the feedstock during above normal years.

5.2.1.2 Trash

As a whole, southern Africa can expect high cellulosic ethanol potentials in above normal years, because of the high yields of cellulose feedstock during these years (Fig. 5.7). While ethanol potentials show a relatively positive increase 25-50KTY (32-63MLY) in most parts of southern Africa, less attractive ethanol potentials (0-25KTY (0-32MLY)) can still be expected in localized areas of the region (Fig.5.7b). This increase in bioethanol potentials over the region during above normal years of cane trash production has a positive influence on carbon dioxide yields (see Fig. 5.7c).

Generally, trash hemicellulose production does not change the ethanol and carbon dioxide production potentials in above normal years, as these potential still remain unattractively low (0-25KTY) (Fig. 5.8).

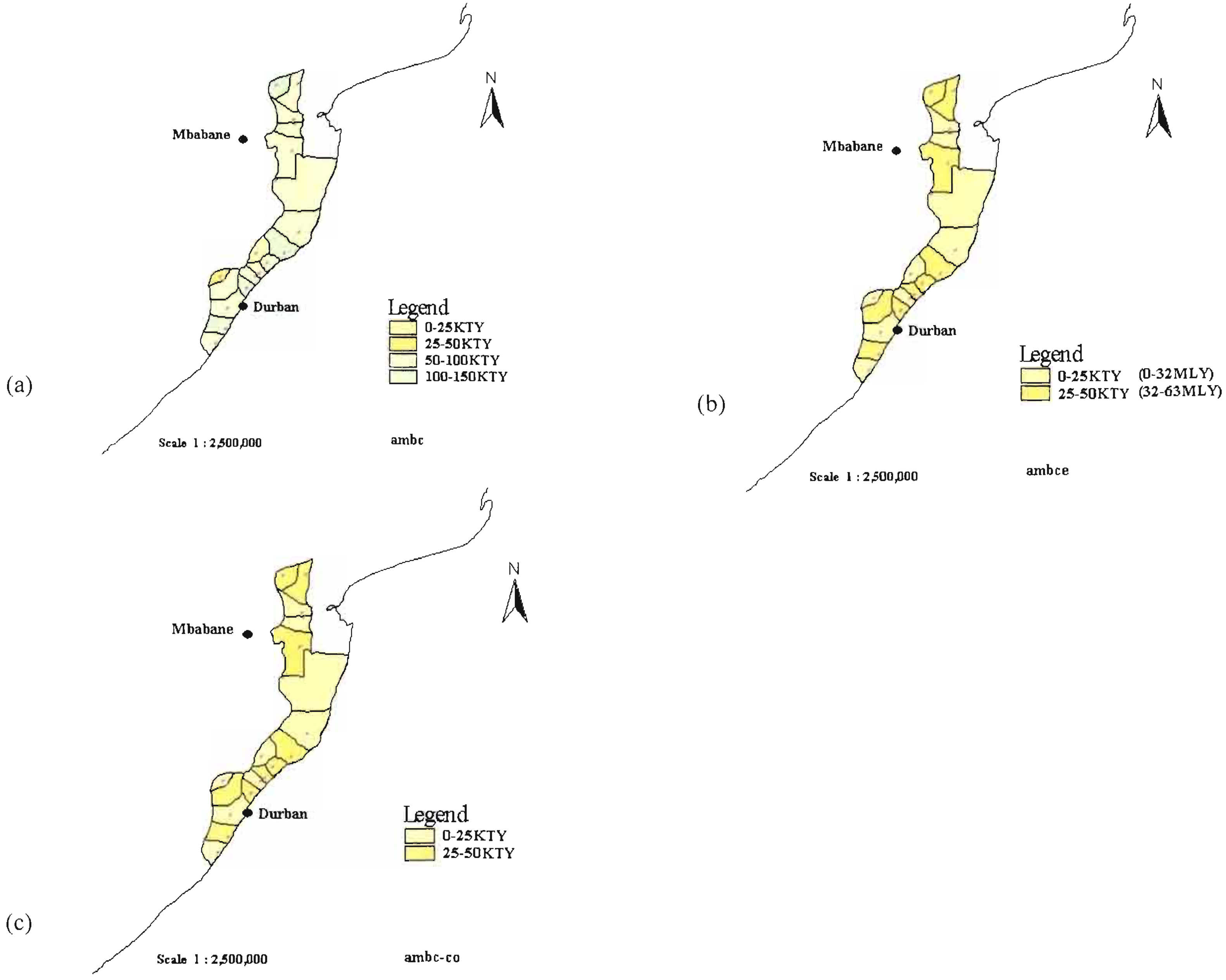


Figure 5.5: Above mean annual bagasse (i.e. mean annual sugar cane yields > normal) (a) cellulosic feedstock, (b) ethanol, (c) carbon dioxide.

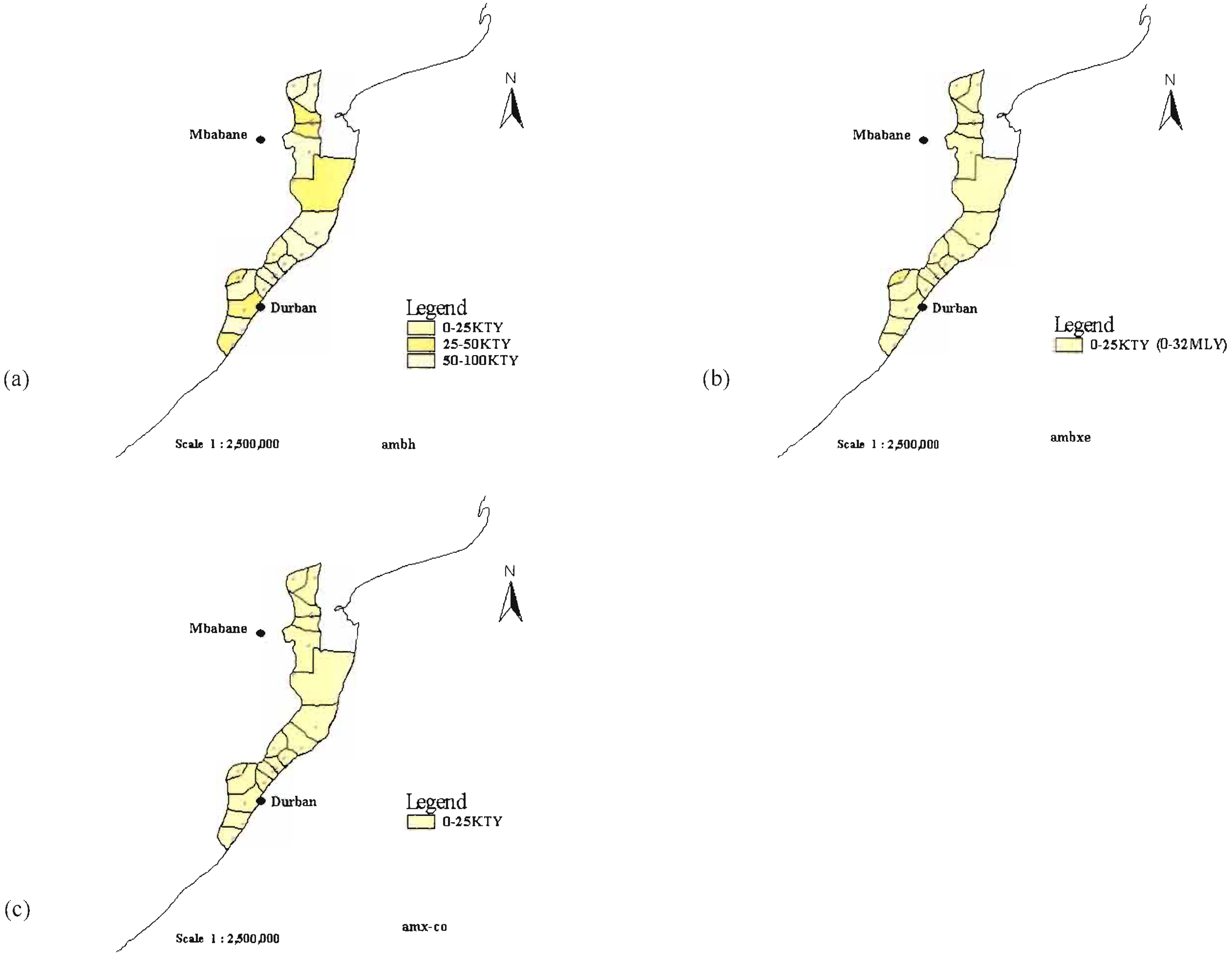


Figure 5.6: Above mean annual: average bagasse (a) hemicellulose feedstock, (b) ethanol fuel, (c) carbon dioxide.

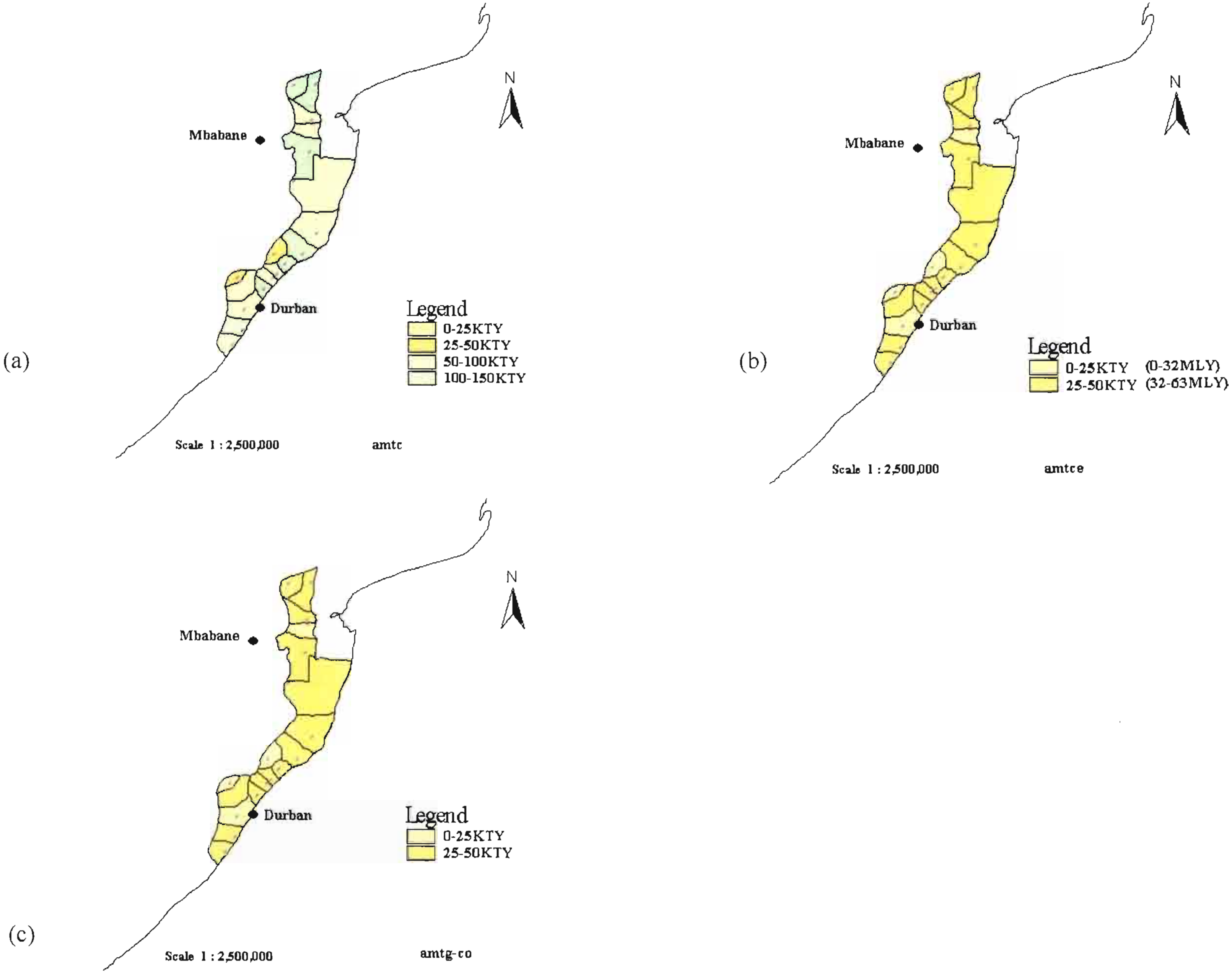


Figure 5.7: Above mean annual: average trash (a) cellulose feedstock, (b) ethanol fuel, (c) carbon dioxide.

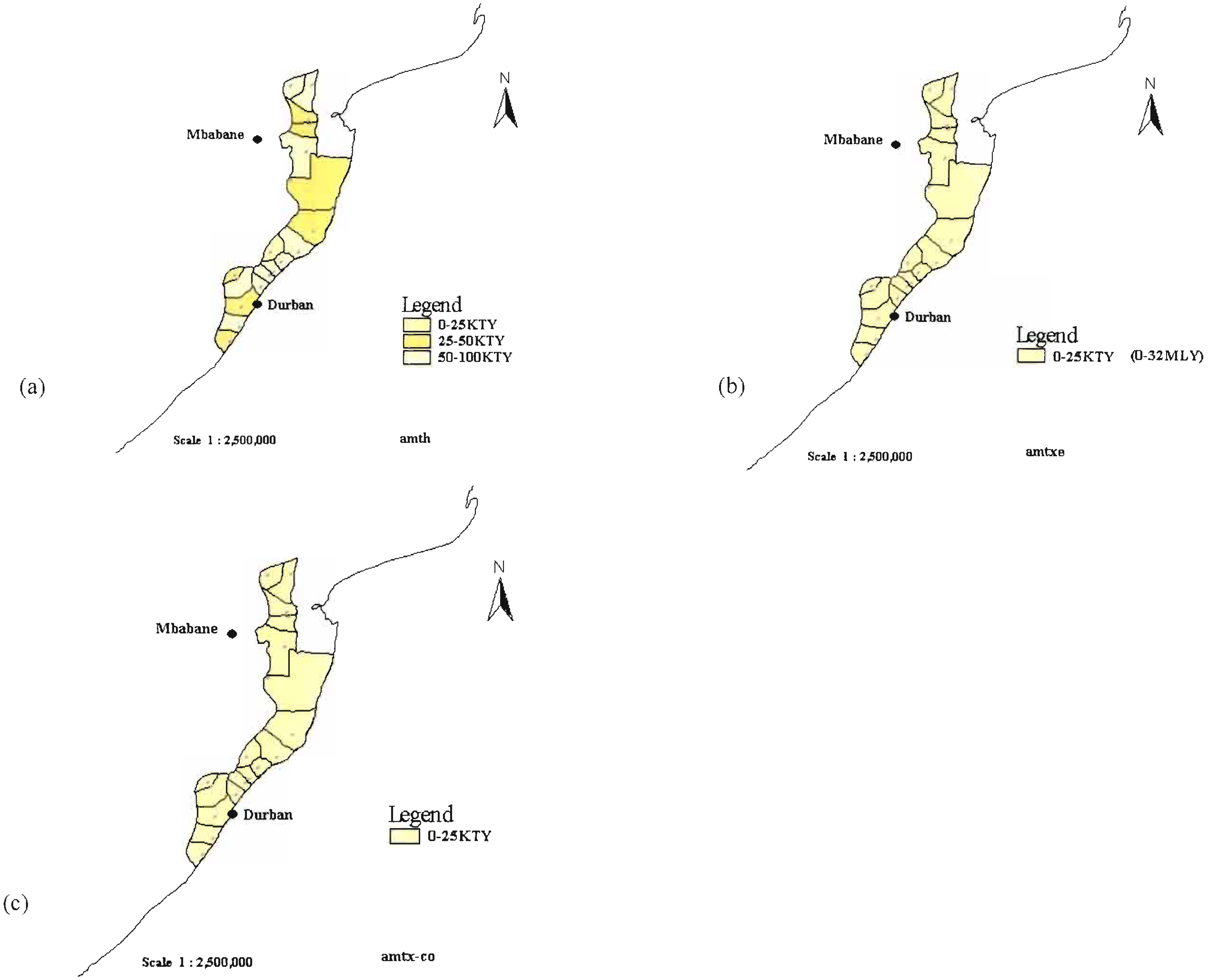


Figure 5.8: Above mean annual: average trash (a) hemicellulose feedstock, (b) ethanol fuel, (c) carbon dioxide.

Having presented the spatial variability of bio-ethanol potentials in years of above normal bagasse and trash production, the discussion will now shift to demonstrate conditions of bioethanol potentials during years of below normal cane production.

Parameters, which need special clarity during below normal years include the extent of event departures from the statistical normals, the spatial variability of these events, as well as the negative implications of these drifts for capital investment in developing the ethanol industry. The success of the analysis can afford better planning and management of poor scenarios in the production of feedstock. The next sub-section clarifies these uncertainties.

5.2.2. Below normal mean conditions

5.2.2.1 Bagasse

While conditions of ethanol potentials during normal and above normal years influence returns on investments, negative departures of ethanol potentials are extremely critical for the viability of the industry during years of not only low production, but also of significantly low sales. Bio-ethanol production, like other agricultural-based industries, can be affected by negative departures of rainfall conditions from normal means. Negative departures of ethanol potentials during below normal years occur in all areas of southern Africa ranging between 0 and 25KTY (0-32MLY) (Fig.5.9b). Hemicellulosic ethanol potentials are still very low during below normal years, a process that is experienced in all parts of the region's sugarcane belt (Fig.10).

5.2.2.2 Trash

Below normal years of trash production significantly reduce annual cellulose, ethanol and carbon dioxide potentials from normal means in southern Africa (Fig.11). Similarly, the region can expect major declines in hemicellulosic ethanol potentials during below normal conditions of trash production (Fig.12).

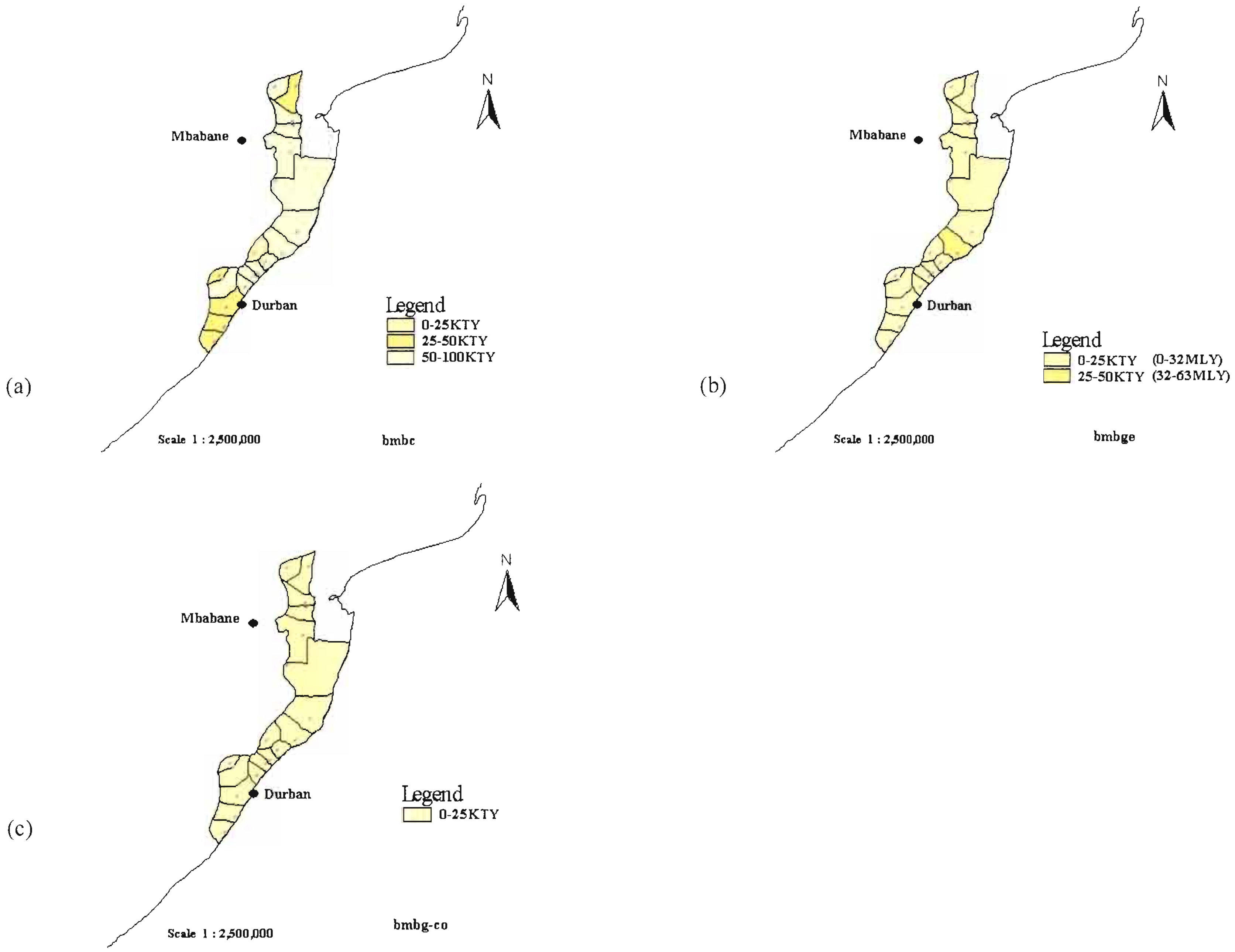


Figure 5.9: Conditions of (a) cellulose, (b) ethanol, (c) carbon dioxide during below normal years of bagasse production.

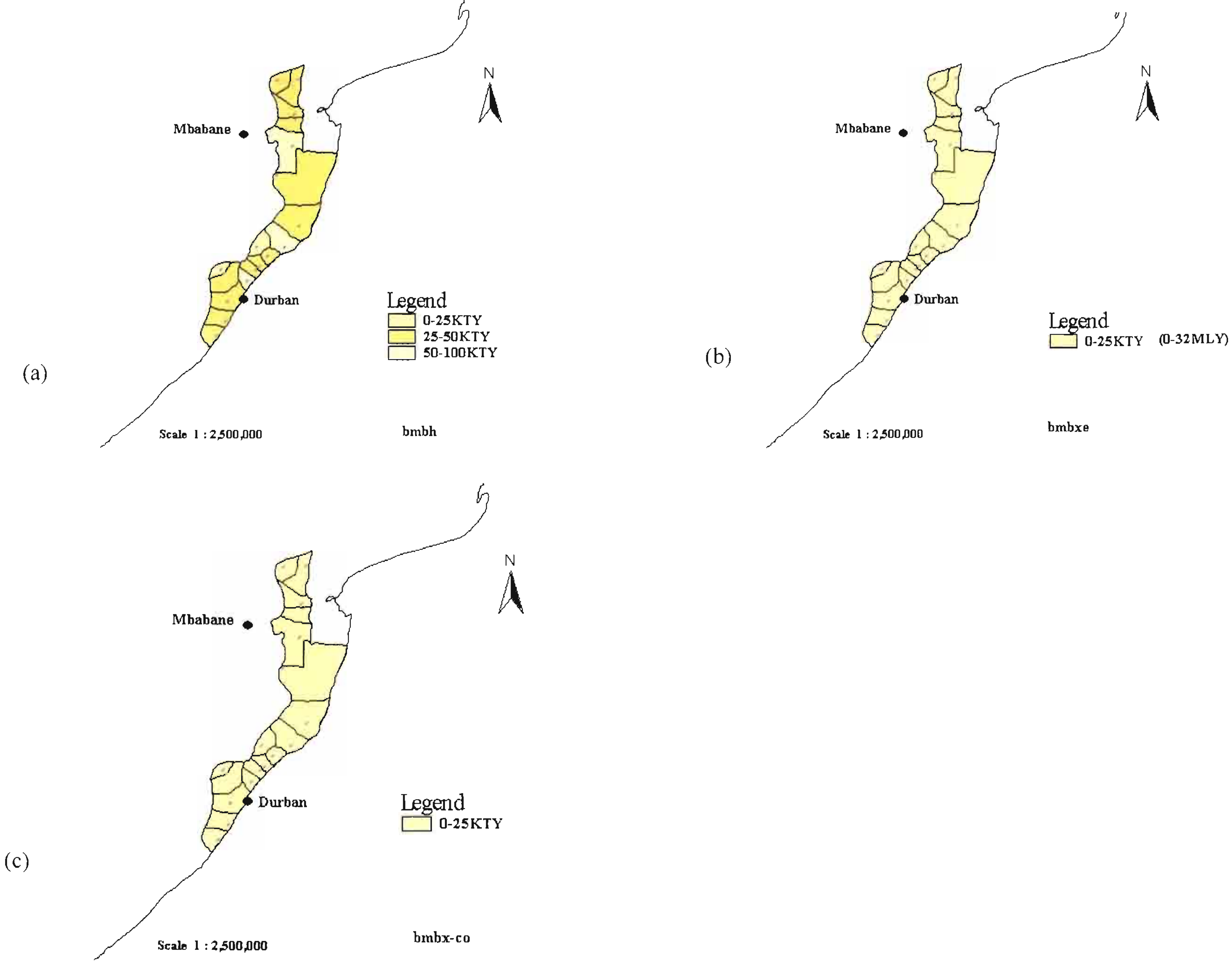


Figure 5.10: Below mean: average bagasse (a) hemicellulose, (b) ethanol, (c) carbon dioxide.

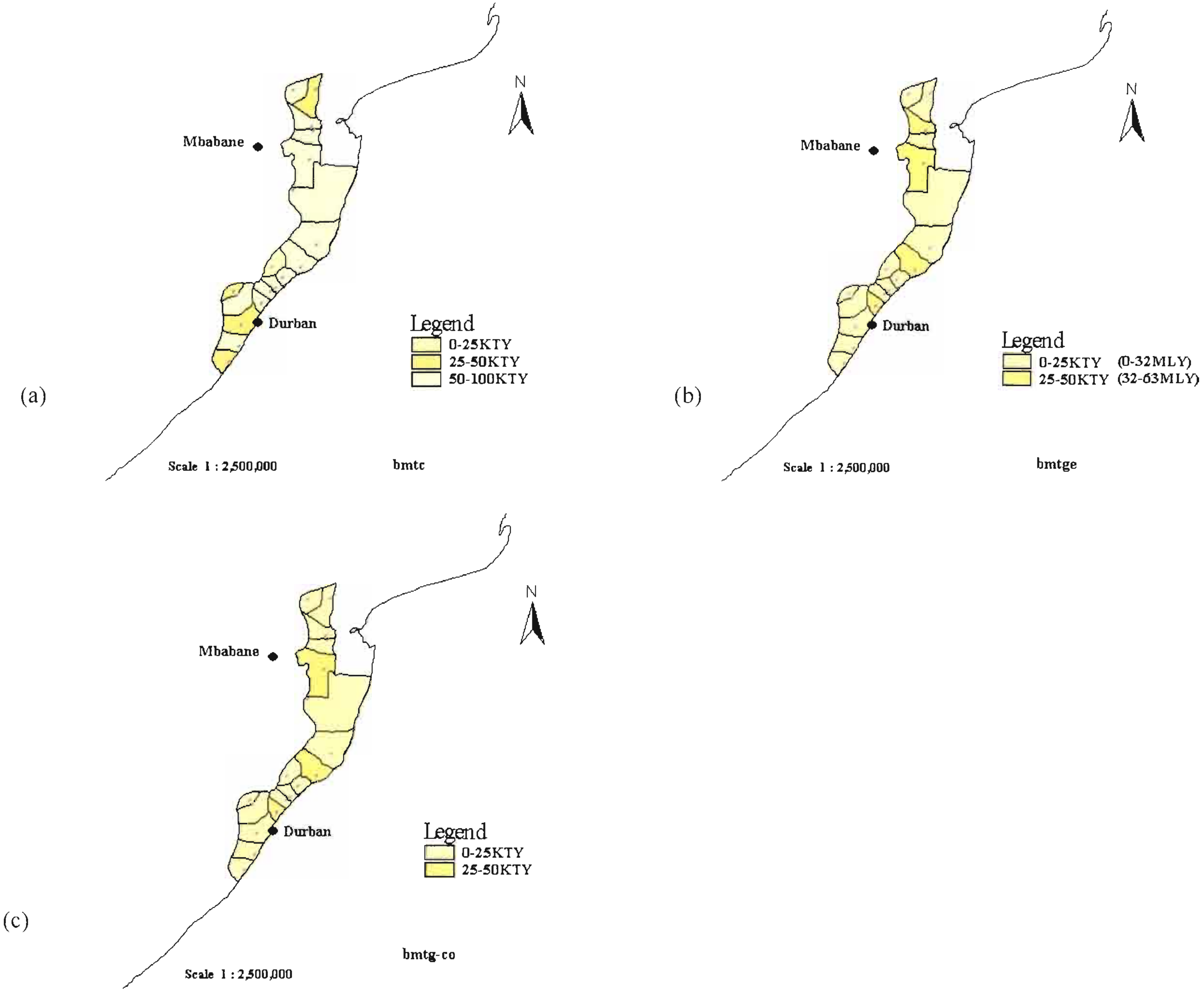


Figure 5.11: Below mean: average trash (a) cellulose, (b) ethanol, (c) carbon dioxide.

Figure 5.12: Below normal conditions: average trash (a) hemicellulose, (b) ethanol, (c) carbon dioxide.

5.3. Summary and Conclusion

Findings presented in this chapter suggest that sugar cane bagasse and trash can be considered as important sources of bio-ethanol fuel in southern Africa. Relatively, the efficiency of trash over bagasse cannot be over emphasized, as both feedstock ethanol potentials closely match in all conditions analyzed in this chapter. Any major difference observed, particularly in above normal years of cellulose production could have resulted from the comparatively higher yields of cane trash (leaf tops and leaves) per unit area (i.e. 17.5bdm% of cane standing biomass). This advantage that trash has over bagasse is cancelled by higher (lower) mass% of bagasse (trash) cellulose and hemicellulose per unit mass of cane crushed. In general, the 2/3 energy ratios of bagasse and trash (1/3 energy ratio each) have been demonstrated by the production potentials of bioethanol fuel from sugar cane, with the remaining 1/3 accounted for by sugar (not analyzed) per unit mass of cane.

Showing the annual conditions of lignocellulosic ethanol potentials during years of above and below normal production for the subcontinent challenges the norm suggesting that the economic viability of sugar cane production is dependent on sucrose yields alone. Facing this important challenge requires intensive future development and management of cane fibre (i.e. in future, sucrose will no longer be the only determinant for research in the development of cane varieties, but also strategies for increasing fibre yields per unit area under cane). The process has major industrial and environmental implications that need not be assessed in isolation. Some of these processes are examined in the next three chapters. The remaining task is identifying sub-regions with better potentials for lignocellulosic ethanol fuel development. Further, impacts of greater bio-ethanol consumption per capita on lands stock potentials for lignocellulosic feedstock (including food crops) production still remain unknown. Before making attempts to clarify these unknowns (in Chapters Seven and Eight respectively), efforts to identify the effects of extreme annual conditions of cane production on lignocellulosic ethanol potentials are made in the next chapter.

Chapter Six

Extreme Annual Conditions of Bio-Ethanol Potentials

6.0 Introduction

Lignocellulosic ethanol potentials during normal years, as well as departures of these potentials above and below annual normal means over southern Africa are now known. However the patterns taken by lignocellulosic ethanol potentials during the extreme years (i.e. years with annual cane yields falling above 75mass% of normal means) are still unknown for the subcontinent. Hence, attempts to identify these conditions are made in this chapter. Given the annual conditions of ethanol potentials in good (above statistical normal mean) and poor (below statistical normal mean) years, this chapter develops an understanding of the variability of lignocellulosic ethanol potentials in extremely high (good) and low (poor) years.

Extreme annual events here refer to those annual cane events falling in the fourth quartiles for the entire length of records covering the 1991 to 2002 period. Extreme annual events further account for the year with the highest, as well as the lowest cane yields over the entire 12-year period of used data for each sugar cane mill. The process shall be shown through an independent analysis of the unique extreme annual events, which comprise of:

(a) extreme high (good) years: average annual yields of all years falling in the 4th quartile (i.e. all annual cane yields > 50% of the statistical normal mean),

(b) extreme low (poor) years: average annual yields of all years falling in the 1st quartile (i.e. those years with annual yields falling below 50% of the statistical normal mean), and finally

(c) the highest, and lowest single year in the studied data set.

Evidence from the previous chapter suggests that good years of cane yields contribute to good years of bio-ethanol potentials, while the opposite results from poor years of cane yields over the whole region. Interest now rests on the remaining unanswered question as to whether extremely good years of feedstock production would result in extremely high ethanol fuel potentials, with the opposite resulting in extremely low production potentials of lignocellulosic ethanol fuel. Of crucial importance to the ethanol industry is the degree of impacts these extreme annual conditions would have on an ethanol plant performance should such events occur in any year.

6.1 Extremely High Annual Conditions

6.1.1 Bagasse

For the period analyzed, extremely high annual cane yields occur in all areas of the southern African sugar cane belt. With a 50KTY of excess bagasse cellulose from the normal mean production in most areas of the region, ethanol potentials are relatively high (25-50KTY (32-63MLY)) in most areas of the subcontinent (Fig.6.1). Experiencing excessively high cellulose yields (100-150KTY) in some areas along the length of the sugar cane belt significantly contributes to the general positive shift in carbon dioxide yields from the statistical normals (Fg.6.1c). Seemingly, hemicellulose ethanol and carbon dioxide production failing to record above 25KTY can be a common experience in southern Africa as a whole not only in normal, above normal years, but also in years of excessively high sugar cane production (Fig.6.2).

6.1.2 Trash

Findings of the analysis suggest that the whole southern African region experiences very high production potentials of trash cellulosic ethanol. While most areas of the region hold the potential of producing between 25-50KTY (32-63MLY), ethanol potentials falling between 50-100KTY (63-126MLY) are experienced in minor areas (Fig.6.3b). In all areas of the region, there is no important shift in ethanol and carbon dioxide potentials during extremely high years as these parameters remain in the range of 0-25KTY (0-32MLY) (Fig. 6.4).

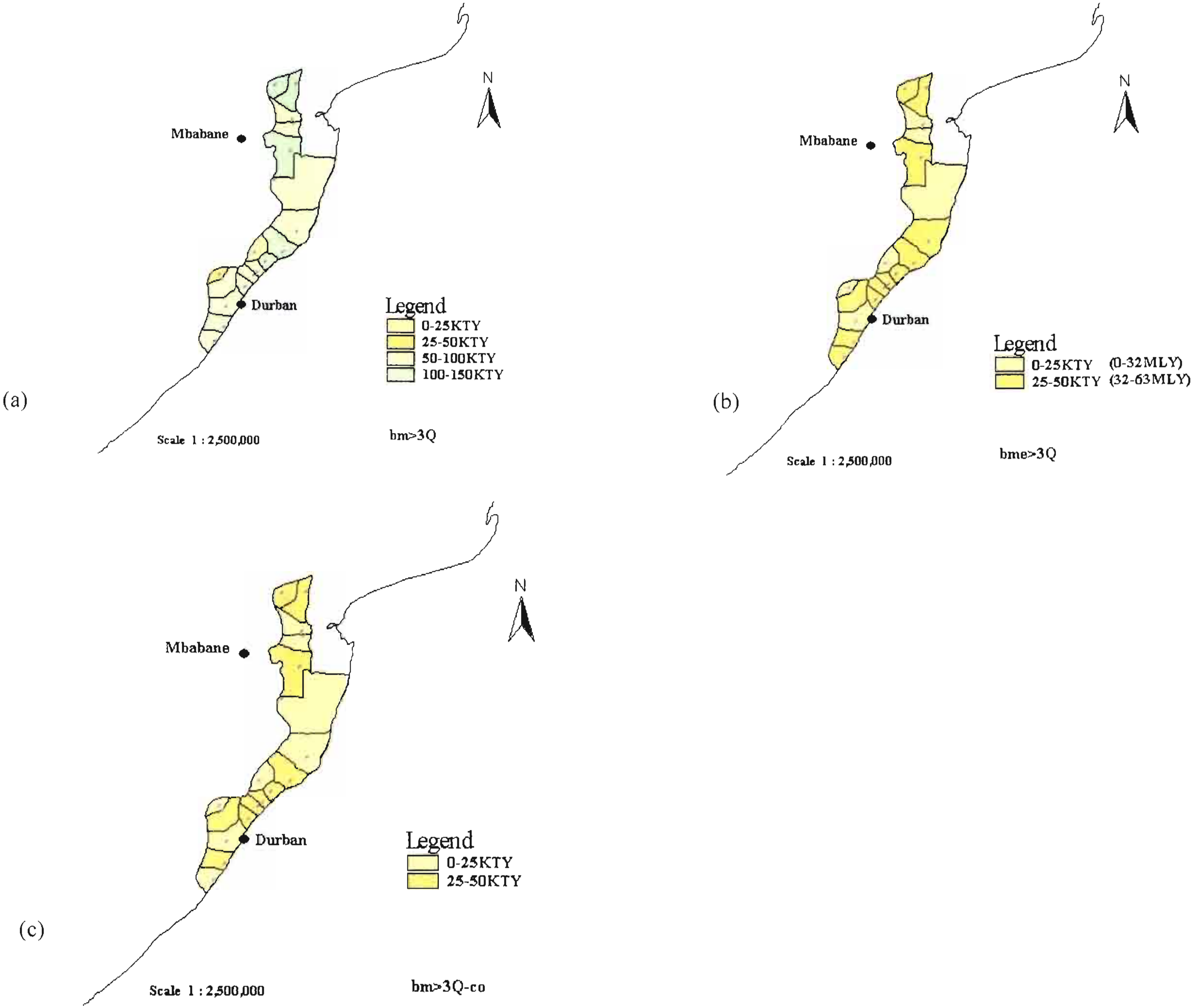


Figure 6.1: Extremely high (i.e. annual cane crushed > 3^{rd} quartile for all years per mill) annual bagasse (a) cellulose, (b) ethanol, (c) carbon dioxide.

Figure 6.2: Extreme high annual cane conditions: average bagasse (a) hemicellulose, (b) ethanol, (c) carbon dioxide.

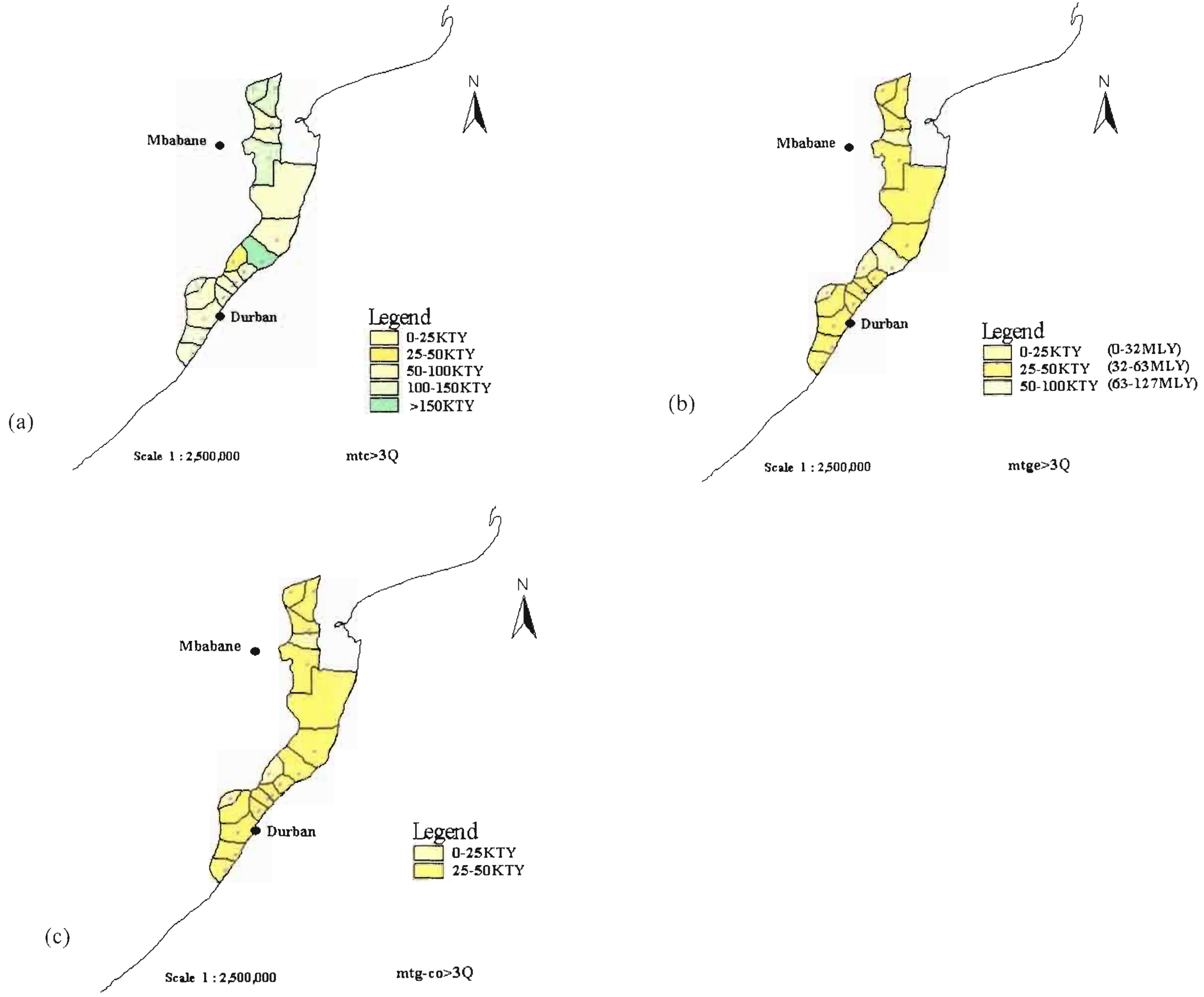


Figure 6.3: Conditions during extremely high trash: average (a) cellulose, (b) ethanol, (c) carbon dioxide.

Figure 6.4: Extreme high annual events of: average trash (a) hemicellulose feedstock, (b) ethanol, (c) carbon dioxide.

Figure 6.5: Extreme low years (i.e. cane yields in the 1st quartile) of: average bagasse (a) cellulose feedstock, (b) ethanol, (c) carbon dioxide.

Figure 6.6: Extreme low annual events: average bagasse (a) hemicellulose feedstock, (b) ethanol, (c) carbon dioxide.

Extremely high annual yields of sugar cane lead to differential inflations of all analysed ethanol production variables over the subcontinent. Trash cellulose has again proven to be very competitive with bagasse as a dedicated feedstock for bio-ethanol fuel production in southern Africa. Despite the accumulation of such invaluable knowledge about the variability of lignocellulosic ethanol potentials for southern Africa, there is still a need to understand the behaviour of ethanol potentials during extremely low years (i.e. the average of cane yields for all years in the entire records of the analysed data falling in the 1st quartile). The presentation given in the following section draws the focus of the discussion to the conditions of extremely low annual events characterising cane lignocellulosic ethanol production.

6.2 Extreme Low Annual Conditions

6.2.1 Bagasse

Extremely low years experience major decreases in the amount of cellulose feedstock and ethanol potentials over the region's cane belt (Fig. 6.5). In most areas of the cane belt, ethanol yields range between 0 and 25KTY (0-32MLY) (Fig. 6.5b). Hemicellulosic ethanol potentials range between 0-25KTY (0-32MLY) (Fig. 6.6).

6.2.2 Trash

Cellulosic ethanol potentials show tremendous declines from normal annual potentials over the whole subcontinent in extremely low years (Fig. 6.7). Similarly, reduced hemicellulosic ethanol and carbon dioxide potentials from normal mean conditions can be expected in the region during extremely low years (Fig.6.8).

Figure 6.7: Extreme low years: average trash (a) cellulose feedstock, (b) ethanol, (c) carbon dioxide.

Figure 6.8: Extreme low years: average trash (a) hemicellulose feedstock, (b) ethanol, (c) carbon dioxide.

6.3 Conditions During Excessively High and Low Individual Years

Having demonstrated the conditions of ethanol potentials for the subcontinent during the extremely high and low years, the discussion now shifts to the extreme departures of ethanol potentials made by a single year in above and below normal years. The highest year refers to the year with the highest cane yields over the analysed period, while the opposite defines the lowest year. Therefore, the highest (lowest) year may vary for the different sugar mills over the region. The spatial occurrence of the highest (lowest) yields in any single year for all mills has not been considered for analysis in the study, because the results obtained would have a negligible contribution in understanding the impact of extreme annual events on the bio-ethanol industry. The assumption is that not all sugar mills in the region would record the highest cane yields in one year, as some may record the opposite.

Over the subcontinent, sugar cane mills more often experienced the highest (lowest) cane yields in different years for the period investigated.

6.3.1 The highest year in the period 1991/92-2001/02

6.3.1.1 Bagasse

Bagasse cellulose production increases in all areas of the subcontinent (Fig.6.9a), and so does the potential to produce ethanol from this feedstock (Fig.6.9b). Ethanol potentials falling in the range of 25-50KTY (32-63MLY) occur nearly everywhere over the sugar cane belt during the highest single year. During this year, carbon dioxide yields range from 25-50KTY in most parts of cane belt (Fig.6.9c). Potentials of hemicellulosic ethanol production range between 0 and 25KTY (0-32MLY) in all areas of the region (Fig. 10).

6.3.1.2 Trash

Cellulosic ethanol potentials from trash increase in all areas of the region (Fig. 6.11). Cellulose yields in excess of 100KTY are clearly showing in most areas of the subcontinent (Fig.6.11a), giving tremendously improved ethanol yields (>25KTY (>32MLY)) all over the region during the highest year (Fig.6.11b). Hemicellulosic ethanol (carbon dioxide) potentials still fall in the range of 0-25KTY (0-32MLY) in all areas of the cane belt during the extremely high year (Fig.6.12).

6.3.2. The extremely low year in the period 1991/92-2001/02

Not only does southern Africa experience major negative drifts in ethanol potentials from statistical normals where bagasse resources are used, but also where trash fibre is considered for ethanol production during an extremely low year of cane production (Figs. 6.13-.6.16).

6.4 Summary and Conclusion

There is now supporting evidence to suggest that extremely high (low) years of sugar cane production can lead to significantly high (low) potentials of lignocellulosic ethanol production over the whole southern African subcontinent. Although related, there is an important value difference between cellulose and hemicellulose in the production of bioethanol fuel. The importance of understanding the effect of extreme feedstock departures from statistical normal means on ethanol potentials has been demonstrated in this chapter. Efficient evaluation of lignocellulosic feedstock in the region (including other parts of the world) therefore requires effective integration of ethanol potentials occurring beyond the spatial and temporal variability of statistical normals. This observation is demonstrated in the next chapter.

Figure 6.9: Conditions during the highest year in the period 1991-2002: average bagasse (a) cellulose feedstock, (b) ethanol, (c) carbon dioxide.

Figure 6.10: Conditions during the highest year in the period 1991-2002: average bagasse (a) hemicellulose feedstock, (b) ethanol, (c) carbon dioxide.

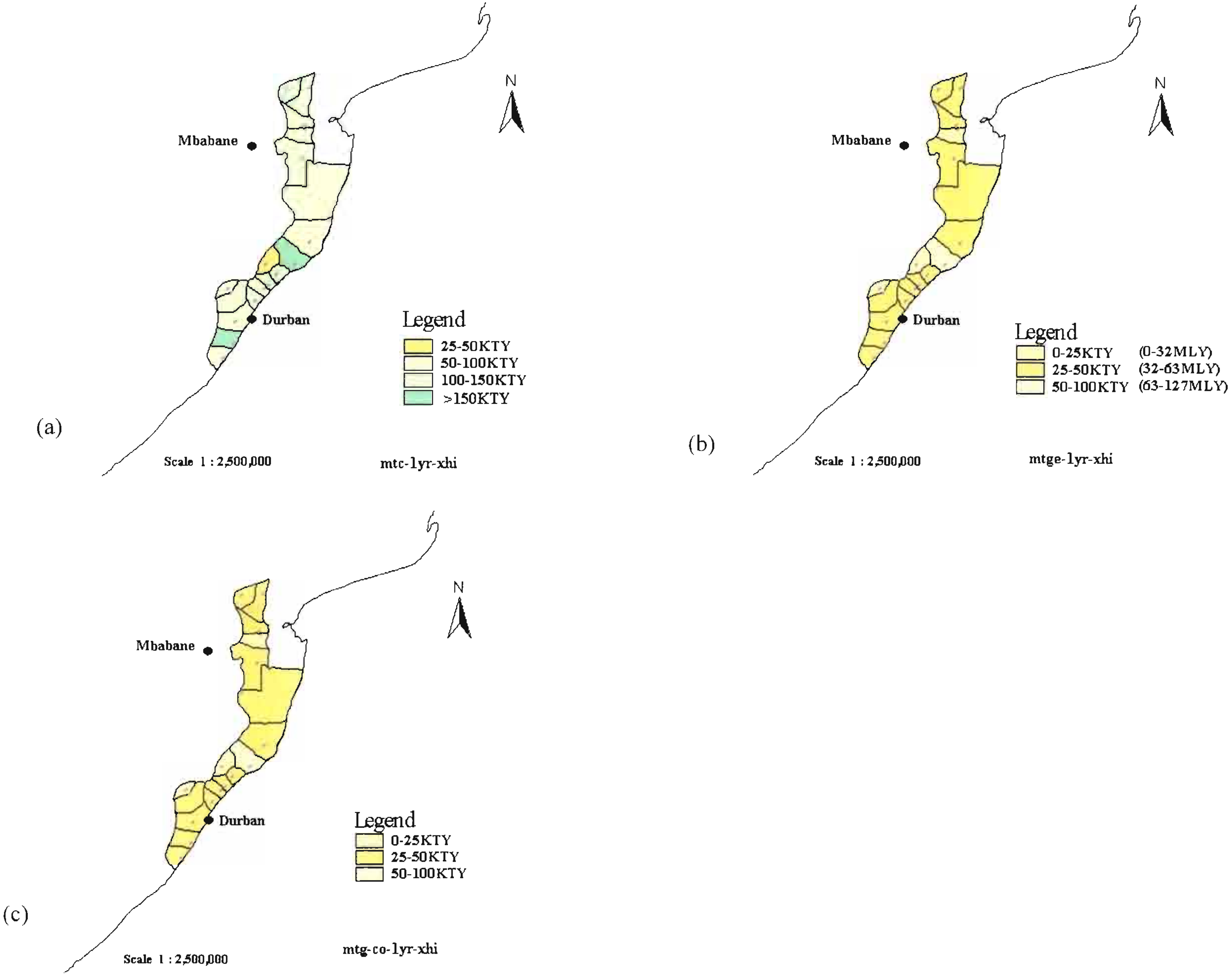


Figure 6.11: Conditions during the highest year in the period 1991-2002: average trash (a) cellulose feedstock, (b) ethanol, (c) carbon dioxide.

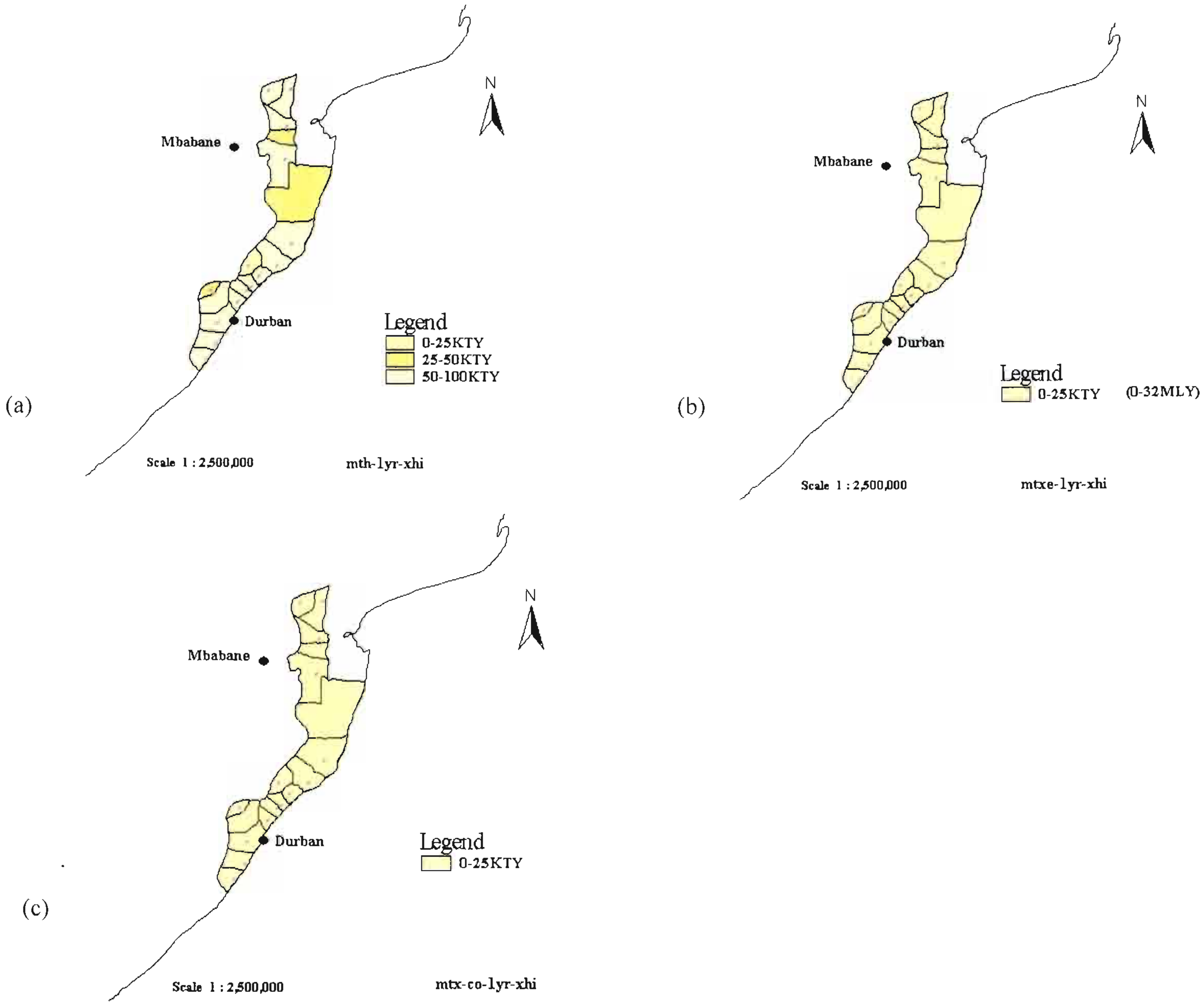


Figure 6.12: Conditions during the highest year in the period 1991-2002: average trash (a) hemicellulose feedstock, (b) ethanol, (c) carbon dioxide.

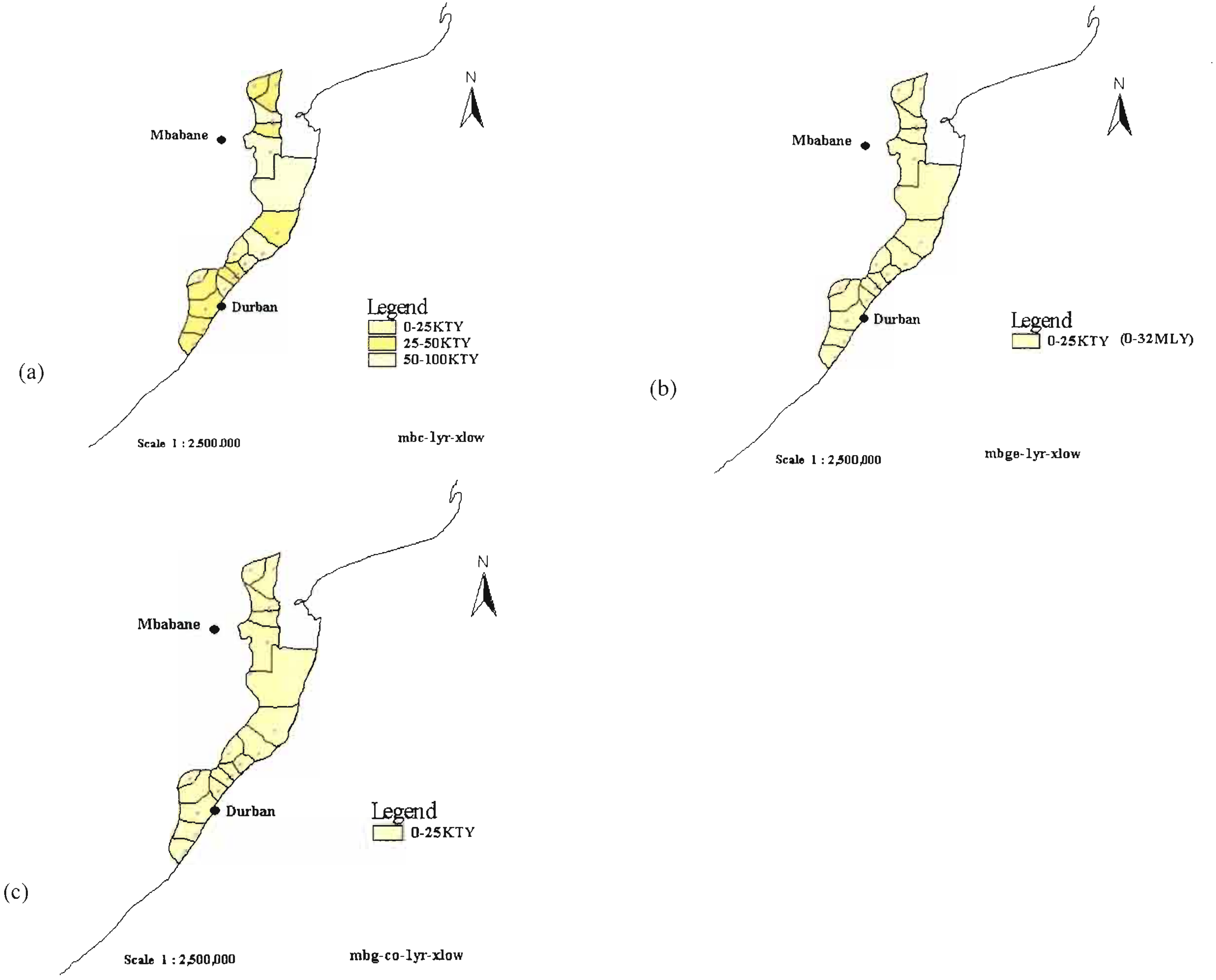


Figure 6.13: An illustration of conditions during the extremely low year in the period 1991-2002: average bagasse (a) cellulose feedstock, (b) ethanol, (c) carbon dioxide.

Figure 6.14: Conditions during the extremely low year in the period 1991-2002: average bagasse (a) hemicellulose feedstock, (b) ethanol, (c) carbon dioxide.

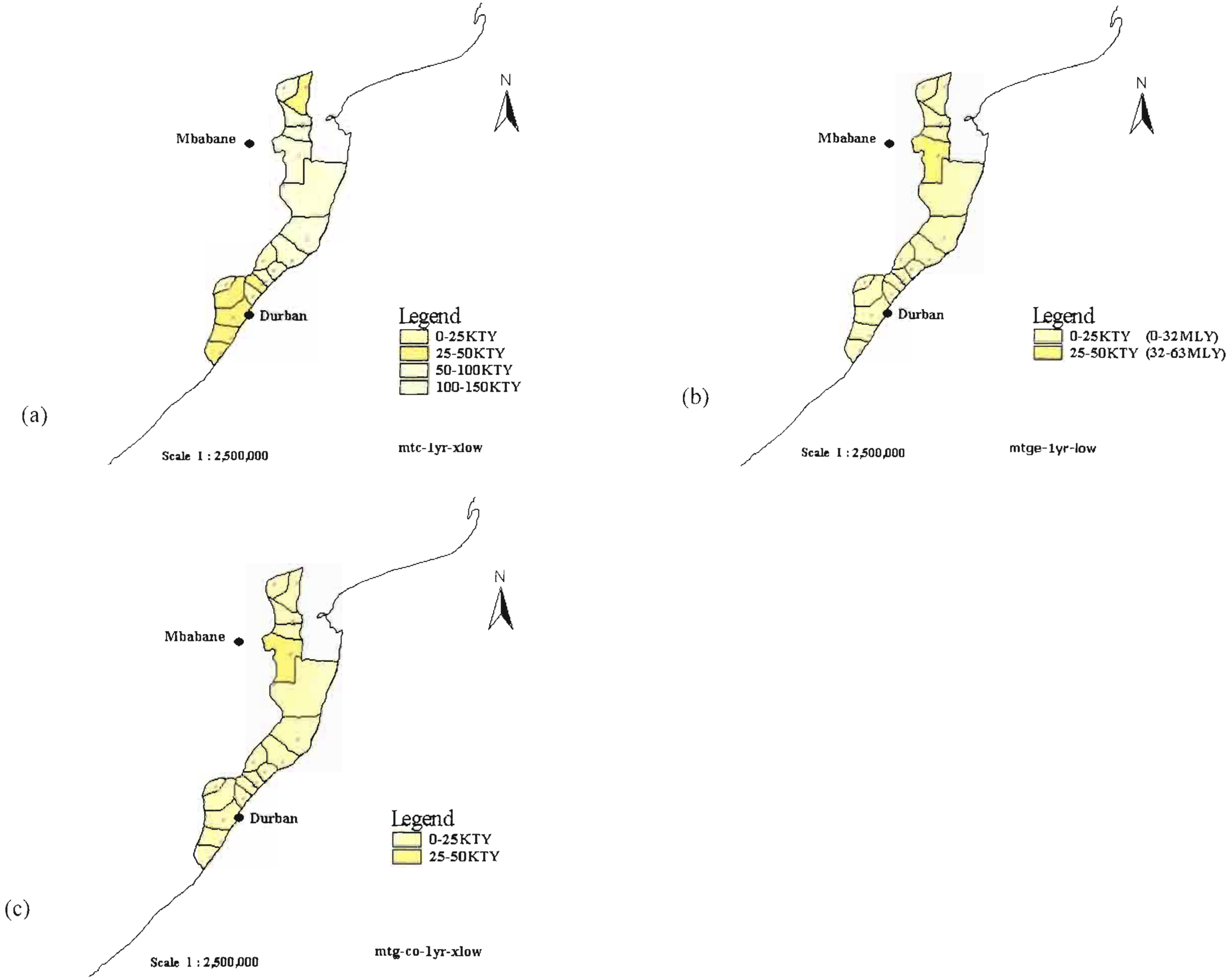


Figure 6.15: Events during an extremely low year in the period 1991-2002: average trash (a) cellulose feedstock, (b) ethanol, (c) carbon dioxide.

Figure 6.16: Events during an extremely low year in the period 1991-2002: average trash (a) hemicellulose feedstock, (b) ethanol, (c) carbon dioxide.

Chapter Seven

Evaluation of Bio-Ethanol Potentials and Market Conditions

7.0 Introduction

Based on the findings presented in the last two chapters, southern Africa has the potential to develop bio-ethanol fuel from sugar cane lignocellulose. However, the potential of the region to produce bio-ethanol fuel from lignocellulose is highly variable in space and time. The question that remains unanswered is whether this spatial variability of bio-ethanol potentials influences the potential distribution of economically viable ethanol plants in the region. If so, the crucial issue is to determine whether efficient capital investment can be achieved in all cane processing areas of the subcontinent given the observed variability of bio-ethanol potentials. The influence of bio-ethanol departures below and above normal mean conditions in locating fuel production plants in the region is demonstrated in this analysis. Processes that would improve the total viability of bio-ethanol production (i.e. optimizing the development of high-value co-product) are briefly discussed in this chapter.

Despite indicating the production potentials of carbon dioxide as a possible byproduct for development, discussing the economic, environmental and industrial implications of producing this gas during bio-ethanol production falls beyond the scope of the study. However, the information provided in this report can be used in future investigations toward developing a better understanding of bio-ethanol fuel production through the fermentation process. This assertion considers that bio-ethanol fuel can also be produced through biomass gasification and ethanol synthesis.

7.1 Bio-Ethanol Economic Analyses

Evaluating the economics of bio-ethanol production from lignocellulose in southern Africa is one of the primary factors directly influencing the viability of the industry as a whole. A simplified approach has been cautiously considered and structured to analyze the economics of lignocellulosic ethanol fuel from sugar cane. The approach comprises of 6 divisions, namely:

(a) economically viable plant size and plant daily operations,
(b) daily, seasonal and annual feedstock requirements and supplies,
(c) feedstock costs and variability,
(d) total production costs of lignocellulosic ethanol,
(e) suitability of the subcontinent's sub-regions to produce lignocellulosic ethanol, and
(f) the total ethanol yields over southern Africa, as well.

7.1.1 The evaluation approach

Shleser (1994), Kerstetter and Lyons (2001) and others have compiled important information for developing a competitive ethanol industry based on the fermentation of lignocellulose. Kinoshita and Zhou (1999) developed an important approach in identifying and evaluating potential sites for bio-ethanol development The United State Department of Energy (U.S.DOE) involvement with the lignocellulose ethanol industry further extends to the co-funding of ethanol demonstration and production facilities, which have benefited this study.

Current industry developments towards commercializing lignocellulose ethanol made by the U.S.DOE have been considered in the industry evaluation process for the southern African region. The economic values of lignin, as the feedstock material for electricity generation have also been considered in the evaluation process. While BBI International (2002) has proposed the co-location of the bio-ethanol plant with a coal-fired power plant instead of a lignin-fired power plant has some economic merits, it has not been considered in this work for the following reasons:

(a) coal, in the large-scale production, is a non-renewable source of energy,
(b) coal combustion increases the atmospheric greenhouse gases, and

(c) the supply of coal can be highly unreliable, as some of the sugar producing countries have very limited coal deposits and variable quality (e.g. Swaziland).

7.1.2 Characterization of lignocellulose ethanol and co-generation plant

Based on the approach and results from the computation of energy and mass balances, as well as capital and operating costs, using computer models created by the U.S. National Renewable Energy Laboratory (NREL), the most effective ethanol plant condition requirements have been identified for the study. There are two primary reasons for NREL to investigate the complete process design and economics of lignocellulosic ethanol plants. Firstly, the process affords the opportunity to direct research by developing a base case of the current process design and economics. Secondly, further investigations enhance the development of an absolute cost of the production of ethanol based on new process and plant design assumptions. In reviewing and establishing research directions, only relative cost differences are important. However, to be able to compare the economics of ethanol with other fuels, the baseline absolute cost is required. To that effect, the best effort has been made to develop cost estimates that are consistent with applicable engineering and construction practices for facilities of this type established in other parts of the world.

To effectively execute the ongoing analysis, the complete processes, including newly researched areas and industry-available process components, have been considered and the cost estimates developed for this work. Adapted from the increasing amount of the most reliable work being done in the U.S. for the current level of lignocellulose ethanol production model design, this study considers the capital cost estimate to be at the conceptual level. Knowledge accumulated from the commercial ethanol plant just ready to become operational using wheat straw and cane bagasse developed by BC International, Inc. will assist in modifying the conceptual to implementable costs in future.

Among the mix of possible bagasse hydrolyzing chemicals, the acid pretreatment with enzyme hydrolysis of cellulose, and co-fermentation of the five and six carbon sugars to ethanol has been adopted for work. A simplified flow diagram showing the basic process is given in Figure 7.1. There are two plant sizes (20 and 40 MGY (76 and 151MLY)), which have been considered in this work for economic investigation. Both plants are assumed to have lignin boiler systems to produce both steam and electricity.

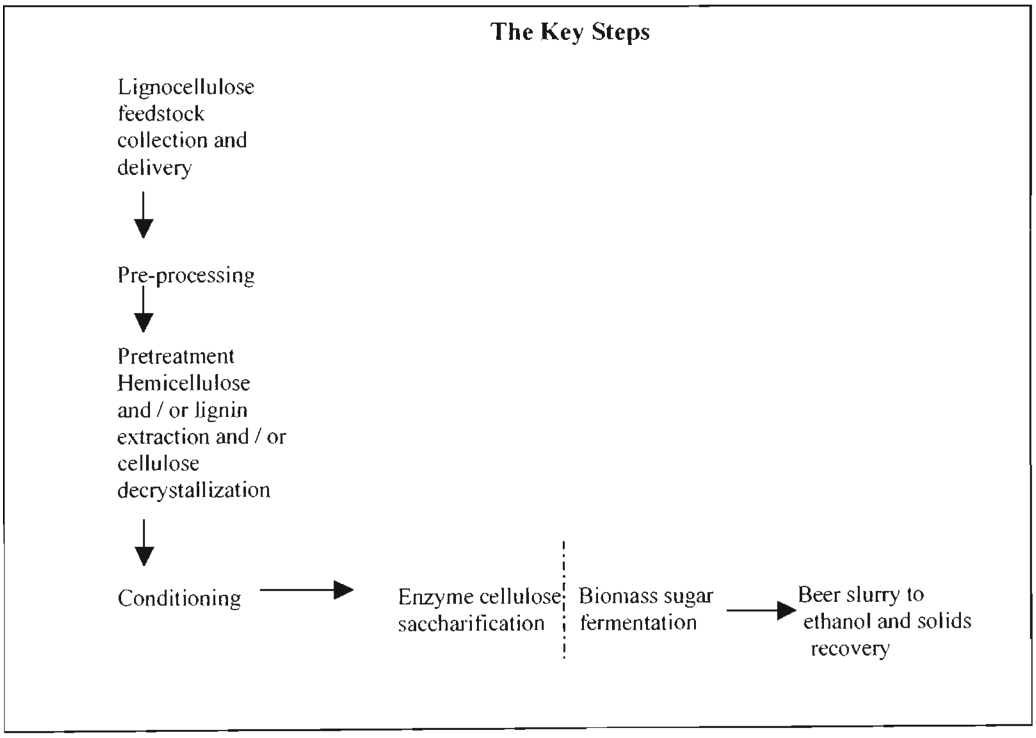


Figure 7.1: An illustration of the key steps to lignocellulose ethanol production.
Source: Elander, 2002.

Realising that southern Africa currently lacks the expertise and technology for commercial conversion of lignocellulose to bio-ethanol, plant costing in this work has been done on the basis of the latest estimates made by the U.S.DOE (1999 U.S. Dollar rate). This approach to estimating costs of a commercial bio-ethanol plant for the conversion of biomass waste is the widely used as the reference internationally. This assumption therefore considers that in establishing the lignocellulose plant in the region, the expertise, equipment and technology would be imported from the U.S.A. Until the expertise and equipment become available in the region, plant cost estimates will be on the basis of plant cost changes achieved internationally.

There has been an exception with the cost estimates for feedstock materials, since these estimates were developed on the basis of feedstock costs in the region. The feedstock costs estimated per ton in the work have considered parameters like feedstock cost to the farmer, feedstock collection, transportation and storage prior to processing. Cost estimates on the basis of feedstock losses prior to processing have been ignored in the study, as the values would be unique for each plant and location. Thus, cost estimates for feedstock materials have been made on the basis of current regional (Swaziland and South Africa) cost evaluations (see Sections 7.1.3 - 7.2). The estimated feedstock costs were then converted to the current U.S. Dollar on the basis of the current exchange rate.

Using the cost estimate approach described above, the equipment cost for the 40 million gallons (151million liters) per year facility is estimated at U.S.$ 103,000,450, with an estimated accuracy that is no better than minus 15% to plus 30%. Since plant cost estimates are still at the conceptual level internationally, which would therefore be relevant for southern Africa at the reconnaissance phase, the factor of 42% to compute the total project investment cost from the installed cost of the equipment has been used. The factor represents the costs to pay for engineering, construction fees, project contingency, as well as site development. The total investment costs for the whole exercise is estimated at U.S.$ 146,260,639 (Table 7.1). Projected annual gross sales of US$68 million can be expected from a 40 MGY plant at the minimal selling price of US$1.70 per gallon (3.785 liters) of ethanol fuel. Although the estimated selling price of 1 gallon (3.785 litres) of bio-ethanol is equivalent to the international estimated selling price, it has been calculated on the basis of the current price gasoline (petrol) in southern Africa. This shows the influence that gasoline products can have on the selling price and market penetration potential of bio-ethanol fuel. The boiler/turbogenerator, being the most expensive equipment, accounts for over one-third of the total capital costs. The integration of the lignin boiler into the ethanol plant certainly offers a positive cost-benefit ratio to the project. A plant with a 40MG annual output can have the capacity to provide all of the steam and electrical daily needs, with an extra surplus of 4.4 kWh of electricity per gallon of ethanol produced (Kerstetter and Lyons, 2001). For electricity to command an attractive price in the national grid, it is necessary to use a boiler/turbogenerator with a very high conversion efficiency acquired at a very competitive cost. Pretreatment and distillation items account for the second highest percentage of the capital costs (Table 7.1).

Table 7.1: Capital costs for a 40 million gallon ethanol facility per annum.

Operation	**Capital Cost (1999 U.S.$)* (2003 South African Rand converted to 2003 U.S.$)**	**Capital cost (%)**
Bagasse feedstock and handling (in South African Rand converted to 2003 U.S$)	6,390,450	4
Pretreatment	14,900,000	10
Neutralization / conditioning	8,800,000	6
Hydrolysis and fermentation	12,400,000	8
Distillation and solid recovery	17,700,000	12
Waste treatment	1,900,000	1
Storage	910,000	1
Boiler/Turbogenerator	36,000,000	25
Utilities	4,000,000	3
Others (estimated @ 42% 0f plant costs)	43,260,189	30
Total equipment cost	**146,260,639**	**100**

Source: Adapted from BBI International, 2002; Kerstetter and Lyons, 2001.

Note: Cost estimates of materials (i.e. feedstock costs) available in southern Africa have been made on the basis of the current material costs in the region. However costs associated with the expertise, equipment and technology would have to be imported to southern Africa at the international estimated costs. Therefore cost estimates of these parameters have been adopted from the international standards, which are most relevant for this reconnaissance analysis.

- The 1999 U.S. $ defines the year on which a very competitive base plant process was designed through which current evaluation processes of large-scale ethanol plant developments are based internationally.

Capital, feedstock, and enzyme production account for most of the operating costs (Table 7.2). The annual costs and the cost for producing one gallon of ethanol are highlighted in Table 7.2. The cost of feedstock would vary from cane bagasse to trash, being the highest with the latter feedstock, with an estimated maximum cost of US 41 cents per gallon. A 40 MGY (151 MLY) plant facility would need 1,500 BDT (1750 BDT) (including feedstock daily losses) of bagasse (trash) at the costs of US$ 0.16 (US$ 0.27) per gallon. The plant would give a daily output of 121,000 gallons (457,985 liters) of ethanol. The theoretical ethanol yield from bagasse is 111.5 gallons per ton. With the conversion efficiency varying from 60 to 90 percent, this gives an average of 70%. The most recent technological development for lignocellulose conversion efficiency to ethanol has improved the average to about 80%. Based on the overall conversion efficiencies of cellulose and hemicellulose suggested in Chapter Four, conservatively, the average conversion efficiency of 70% has been used for economic analysis (see Chapter Three). To improve returns from the investment, the plant would operate for 330 days in a year.

Capital related costs account for a major part of the operating costs, which are shown in Table 7.2 as the depreciation costs (i.e. representing recovery of capital and return on investment). If the ethanol development facility can be financed from loan dollars at rates lower than the required return on equity rate, a reduction in operating costs would come automatically. The effects of the various financing options on the minimum ethanol-selling price are quite evident. Lower interest rate and the increased time period of the loan further reduce the minimum-selling price of one gallon of ethanol fuel considerably.

Based on the suggestions made by Aden *et al.* (2002) and Kerstetter and Lyons (2001), the selling price of $0.013/kWh, although high for southern Africa, has been assumed for the 40 million gallon ethanol facility. Should lignin electricity be accredited as green energy, the product can certainly command higher market prices. However, the latter assertion cannot be considered in the analysis, since higher costs would reduce the market size in a developing world, such as southern Africa. There is a very interesting relationship between the selling price of ethanol and that of electricity (Fig. 7.2). Assuming that the generated electricity commands a selling price of $0.04/kWh, the minimum price for ethanol would be reduced by over $0.10/gallon.

Table 7.2: Capital costs for a 40 million gallon ethanol facility per annum.

Operation	**Capital Cost (1999 U.S.$) (2003 South African Rand converted to 2003 U.S.$)**
Bagasse (495K BDT/year @ $12.91 per BDT) (in S. A. Rand converted to 2003 U.S$)	6,100,000
Enzymes	6,300,000
Other raw materials	4,000,000
Waste disposal	1,200,000
Electricity	-2,300,000
Fixed costs	6,900,000
Capital depreciation	9,000,000
Total	**31,200,000**

Source: Adapted from Kerstetter and Lyons, 2001; BBI International, 2002.

The above given analysis of the conditions of the electricity generated by the facility, assumes that all the produced lignin is used for the purpose. The issue would certainly be different, where the development of high-value lignin products is considered. Should this be the case, the co-product development process would still contribute to the reduction of the production costs per ethanol gallon, thus effecting a further reduced minimum-selling price per gallon of ethanol fuel.

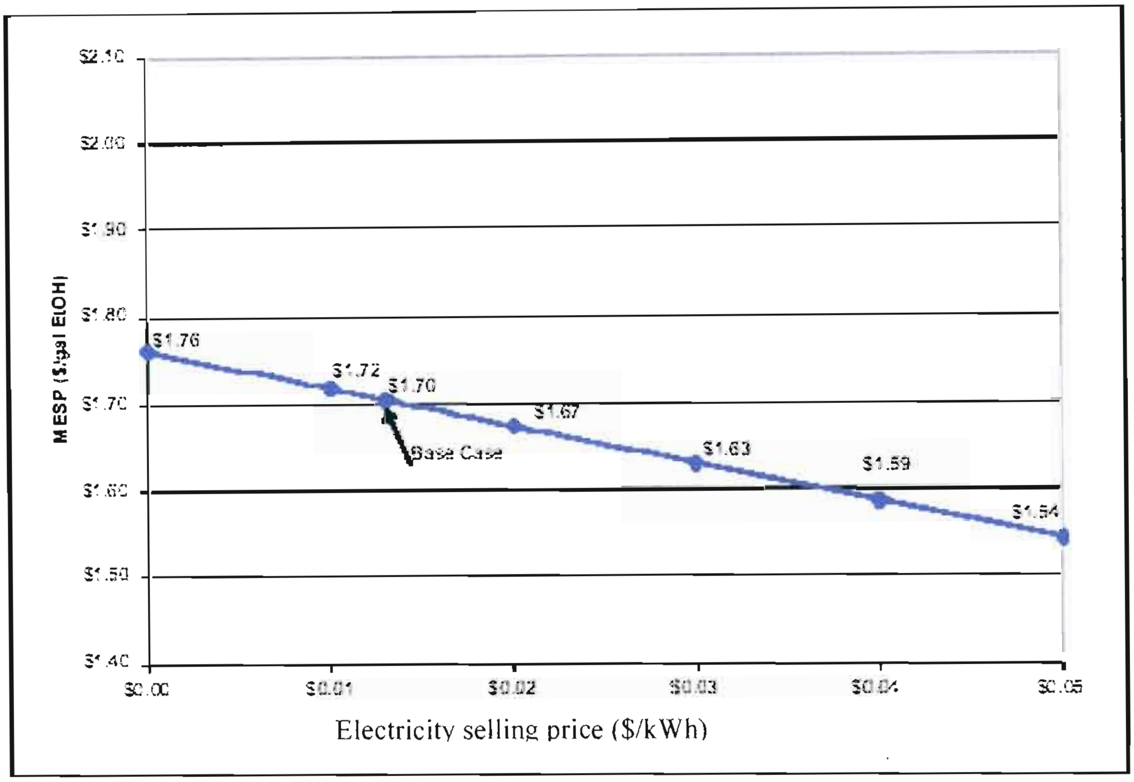


Figure 7.2: Electricity price sensitivity analysis.

Source: Kerstetter and Lyons, 2001.

The importance of the economy of scale has been shown with the U.S.A. corn ethanol plants. Small ethanol plants would lead to lower feedstock costs and increased bio-ethanol selling prices per unit, as the market demand of this product would be high. Kerstetter and Lyons (2001) suggested the minimum selling price of $1.93/gallon for a 20 million gallon facility compared to $1.70/gallon (3.785 litres) for the 40 million gallon facility. The selling price of bio-ethanol produced using a smaller plant would be much higher than the selling price of gasoline products (e.g. petrol), making bio-ethanol fuel less competitive in the transport market. The minimum selling price of bio-ethanol per gallon (litre) is to a large extent dependent on the price of gasoline, which needs to be more competitive with that of conventional fuels. In Brazil, for example, low gasoline prices directly reduced market demand for pure bio-ethanol fuel leading to an almost zero sale of pure ethanol cars in 1996 (see Moreira and Goldemberg, 1999). Further, the dependence on policies by the Brazilian ethanol fuel industry on policies to regulate ethanol prices over the long-term compromised the competitive business aspect of developing bio-ethanol fuel. This dependence had a major contribution to the fall in annual sales of hydrous bio-ethanol fuel. The opposite is observed in the U.S.A. where the direct influence of gasoline prices has been considered during the initial phase bio-ethanol prices through the provision of incentives and subsidies, making this fuel competitive with gasoline (see Chapter 8 for details). This has allowed consumers (automakers and car owners) to accept and promote the development of bio-ethanol fuel in a business environment.

7.1.3 Conditions of feedstock cost

Bio-ethanol fuel adds value to resources such as bagasse and trash initially having no economic values attached to benefit farmers. The minimal bagasse feedstock cost is therefore estimated at US$ 0.16 per gallon of ethanol (i.e. using regional cost estimates of feedstock) in this analysis. The inclusive cost of bagasse is therefore estimated at US$12.91 per ton to produce about 70 gallons of ethanol (i.e. using regional cost estimates of feedstock). A different method can be used to calculate the cost of trash feedstock, as this cane resource currently has no value to the farmer.

7.1.4 Trash supply analysis

Trash ethanol production requires that green cane harvesting is adopted in the region, and more efficient harvesting methods are practiced as well. The cost of supplying trash to fuel producers has been given a general estimation for the region. Delivery cost of cane trash, consisting of collection, transportation, storage, handling as well as payment to the farmer, significantly influences the selling price of bio-ethanol fuel (Fig. 7.3).

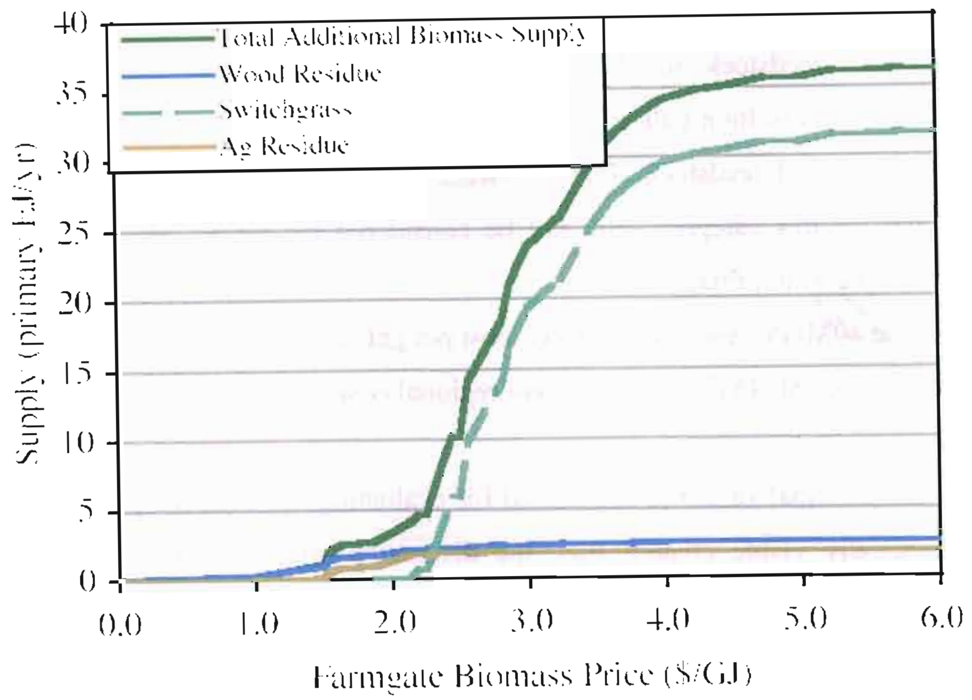


Figure 7.3: Illustration of a biomass supply curve: supply is given in terms of primary biomass at the 'farm gate' before any transformation or transportation based on corn stover.

Source: Smith *et al.*, 2004.

7.2 Screening and Evaluation of Sugar Mills

7.2.1 Screening

Based on the analysis given in the preceding section, requisites for locating bio-ethanol plants based on lignocellulose as the dedicated feedstock include:

1. the sub-region must have sufficient lignocellulosic feedstock to produce 40 million gallons plus 5% of the total per annum during normal years (i.e. 2 MGY + 40 MGY = 42 MGY of ethanol),
2. during conditions of below normal events, the decline from the standard yield of 40 MGY of ethanol should not exceed –5% of this volume (i.e. -2 MGY + 40 MGY = 38 MGY of ethanol),

3. average conditions during the extreme low events must not reduce the annual ethanol yields of 40MG by over 10% i.e. 4 MGY of ethanol),
4. areas having feedstock supplies during below normal events that meet the production of 20 million gallons can be considered only where sufficient land for growing dedicated feedstock (such as sweet sorghum) is available (sub-regions qualifying for this category shall not be considered for further analysis in the current chapter), and finally
5. to meet the 40MGY, average feedstock cost per gallon of ethanol for a sub-region must not exceed $0.45 (i.e. using current regional cost estimates of feedstock).

Given the principal variables considered for evaluating sub-regional potentials to produce economically viable ethanol fuel, the discussion will now show suitability classes towards the development of bio-ethanol plants in southern African as a whole.

7.2.2 Evaluation of mills

As shown in preceding chapters, southern Africa shows a significant spatial variability for ethanol production. Feedstock conditions during normal events, as well as the drifts taken by feedstock conditions in below normal years stand as the principal factors determining the viability of lignocellulosic ethanol production over the whole southern African region. The economics, environmental factors and markets become secondary parameters to influence the evaluation process of ethanol production at sub-regional scale.

Following the prime factors for bio-ethanol evaluation shown above, southern Africa has been divided into eighteen (18) sub-regional segments (cane mill catchments) for the evaluation process. Based on the first criteria for sub-regional classification, only six (or eight in cases where new developments in mills currently meet feedstock requirements not reflected in all historical records used in the analyses sub-regions qualify for further analysis (see Table 7.3 to 7.4). The Komati and Mhlume sugar cane mills have undergone significant expansion in the last few years (resulting from the construction of Driekopies and Maguda Dams) where the average cane yield records used in the analyses as a whole include years with cane area below the current totals. It is for this reason that the two sub-regions receive positive values and therefore qualifying for further evaluation (Table 7.3).

Table 7.3: The influence of feedstock conditions on ethanol during normal years.

SCENARIO 1

Mill	**Plant Size (MLY)**	**Total bagasse-trash EtOH (MLY)**	**Fibre EtOH of 159 MLY[1] (%)**	**Cane (Sweet sorghum) sugar EtOH (% of 159MLY)**	**Classification**	**Description**
Komati*	151.4	83.5	52.5	47.5	1	Suitable for consideration
Mhlume*	151.4	78.2	49.2	50.8	1	Suitable for consideration
Simunye	151.4	63.4	39.9	60.1	-1	Not Suitable for development
Ubombo Ranches	151.4	93.8	59.0	41.0	1	Suitable for consideration
Pongola	151.4	70.8	44.6	55.4	-1	Not Suitable for development
Umfolozi	151.4	73.9	46.5	53.5	-1	Not Suitable for development
Felixton	151.4	123.3	77.5	22.5	1	Suitable for consideration
Malelane	151.4	93.9	59.1	40.9	1	Suitable for consideration
Entumeni	151.4	18.3	11.5	88.5	-1	Not Suitable for development
Amatikulu	151.4	97.9	61.6	38.4	1	Suitable for consideration
Darnall	151.4	79.6	50.1	49.9	0	Very sensitive
Glenhow	151.4	73.6	46.3	53.7	-1	Not Suitable for development
Maidstone	151.4	107.2	67.4	32.6	1	Suitable for consideration
Nooddberg	151.4	76.2	47.9	52.1	-1	Not Suitable for development
Union Coop	151.4	42.6	26.8	73.2	-1	Not Suitable for development
Eston	151.4	62.5	39.3	60.7	-1	Not Suitable for development
Sezela	151.4	108.0	67.9	32.1	1	Suitable for consideration
Umzimkhulu	151.4	68.0	42.8	57.2	-1	Not Suitable for development

Fibre EtOH (ethanol) of 159 MLY[1]: Assurance feedstock supply exceeds required plant capacity by 5%, which is 159MLY.

* Sugar mill either does not meet the criteria for classification or falls short of the current ethanol potential not reflected in the data used. These mills have undergone major recent expansions in cane production to meet the criteria for classification.

Except for only five areas, all of the southern African sub-regions do not produce sufficient lignocellulose feedstock to meet the feedstock requirements for a 40 MGY (151MLY) plant during average conditions of below normal drifts (Table 7.4). It is quite evident that the occurrence of extremely low conditions of feedstock production would have tremendous negative impact on ethanol production over the whole southern African region (Table 7.5).

Table 7.4: Average conditions of ethanol production during below normal years.

SCENARIO 2

Mill	**Required Plant Capacity (MLY)**	**Total bagasse-trash EtOH (MLY)**	**Assurance plant capcity (+5%) (MLY)**	**Fiber EtOH production (%)**	**Cane (S. sorghum) sugar EtOH (%)**	**Classification**
Komati	151	45	159	28	72	*-1*
Mhlume	151	76	159	48	52	*1*
Simunye	151	60	159	38	62	-1
Ubombo Ranches	151	83	159	53	47	1
Pongola	151	61	159	38	62	-1
Umfolozi	151	66	159	41	59	-1
Felixton	151	87	159	55	45	1
Malelane	151	73	159	46	54	-1
Entumeni	151	16	159	10	90	-1
Amatikulu	151	74	159	47	53	-1
Darnall	151	65	159	41	59	-1
Glenhow	151	60	159	38	62	-1
Maidstone	151	85	159	54	46	1
Nooddberg	151	66	159	42	58	-1
Union Coop	151	36	159	23	77	-1
Eston	151	49	159	31	69	-1
Sezela	151	54	159	34	66	-1
Umzimkhulu	151	43	159	27	73	-1

* Sugar mills, which do not qualify according to the long-term data analyzed, but do qualify considering the long-term implications of the major recent expansions in cane production not reflected in the data used.

Presented with the above final evaluation of the region as a whole to produce ethanol fuel, only two sub-regions (Mhlume and Felixton) have the potential to meet all the renewable lignocellulose feedstock requirements to ferment 40 million gallons of ethanol annually. The qualification of four more sub-regions is dependent on the availability of supplementary feedstock during the extreme low years to meet raw material requirements for the standard annual ethanol yield per plant. Sweet sorghum is considered as one of the potential supplementary feedstocks for sub-regions characterized by greater feedstock supply risks during the extremely low years. The analysis of sweet sorghum as the potential supplementary feedstock, where cane lignocellulose availability becomes constrained during some parts of the year is not considered in this study. The issue must be given special attention in future research.

Table 7.5: Average conditions of ethanol production during extreme low years and the overall suitability classes.

				SCENARIO 3			
	Total bagasse-	**Plant size (-10%)**	**Fiber EtOH**	**Cane (S. sorghum)**	**Classification**	**No. of S=1 in**	**Suitability**
Mill	**trash EtOH – 1Q (MLY)**	**of normal (MLY)**	**(% of 136.3MLY)**	**sugar EtOH (%)**		**Scenarios 1-3**	**Class (final)**
Komati	39.0	136.3	28.6	71.4	-1	1	S3
Mhlume	74.2	136.3	54.5	45.5	1	3	S1
Simunye	57.2	136.3	42.0	58.0	-1	0	N
Ubombo Ranches	26.7	136.3	19.6	80.4	-1	2	S2
Pongola	58.7	136.3	43.1	56.9	-1	0	N
Umfolozi	57.6	136.3	42.3	57.7	-1	0	N
Felixton	77.0	136.3	56.5	43.5	1	3	S1
Malelane	64.2	136.3	47.1	52.9	-1	1	S3
Entumeni	13.0	136.3	9.6	90.4	-1	0	N
Amatikulu	70.5	136.3	51.7	48.3	1	2	S2
Darnall	59.2	136.3	43.5	56.5	-1	0	N
Glenhow	52.3	136.3	38.4	61.6	-1	0	N
Maidstone	67.2	136.3	49.3	50.7	-1	2	S2
Nooddberg	54.3	136.3	39.9	60.1	-1	0	N
Union Coop	32.2	136.3	23.7	76.3	-1	0	N
Eston	43.2	136.3	31.7	68.3	-1	0	N
Sezela	53.8	136.3	39.5	60.5	-1	0	N
Umzimkhulu	42.6	136.3	31.3	68.7	-1	0	N

1Q: 1st quartile

ETOH: ethanol

N: not suitable (i.e. mill's annual ethanol production is < 50% of scenario 3 criteria)

S1: very suitable (i.e. mill's annual ethanol production is >75% of scenario 3 criteria (or suitable in all three scenarios))

S2: suitable (i.e. mill's annual ethanol production falls between 50-75% of scenario 3 criteria)

The presentation given in the chapter thus far has shown the economics and the different suitability classes for the various sub-regions of the subcontinent to produce ethanol from cane lignocellulose. Highlights of the spatial and temporal market characteristics still remain the missing piece of the lignocellulosic ethanol puzzle over the region. The next section will attend to the unsolved segment of the puzzle.

7.3. Characteristics of Ethanol Markets

Partnership between the petroleum and the ethanol fuel is necessary to create ethanol fuel markets. In developing this business partnership, the (a) non-dependable supply, (b) increased volatility prices, (c) lack of control on production, (d) decreasing quality, as well as (e) increased dependence on foreign gasoline have to be considered.

The market analysis given in the section considers various parameters, among which are:

(a) promoting more efficient ethanol/gasoline fuel blends as per market characteristics,
(b) promoting the use of more efficient motor technologies that increase ethanol fuel consumption per unit time, such as the U.S.A. E85 flexible fuel vehicle (FFV) that can run on pure gasoline or fuel blends containing up to 85% ethanol in gasoline,
(c) the need to promote regional energy security,
(d) regional economic growth and development through agricultural market development, and finally
(e) promoting increased participation of the private sector in the development of the industry.

Given these principles upon which the market analysis has been based, this analysis will henceforth focus show bio-ethanol market conditions in region. Using data for gasoline sales over a nine-year period for South Africa and a six-year for Swaziland (see Chapter Four), ethanol/gasoline blending ratios analyzed are E10, E12, E15 and E24 where. These are mixtures of 10vol%, 12vol%, 15vol% and 24vol% ethanol in gasoline, respectively. The analysis further considers the important market limitations associated with the E12 and E15 fuel blends, as the scale of bio-ethanol fuel consumption cannot balance the costs for industry development and petrol engine modification. Potential ethanol markets depend on:

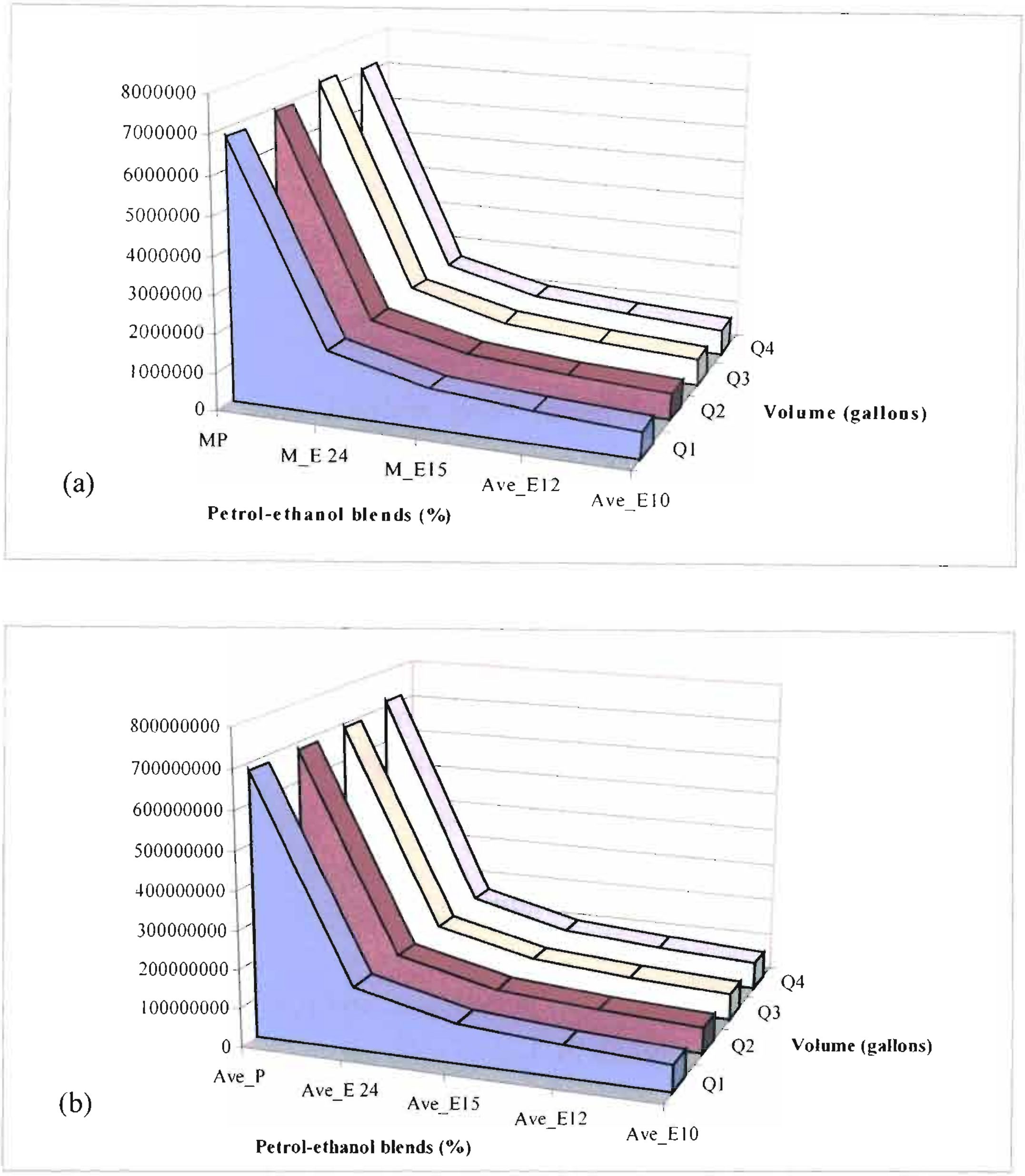
(a) mean annual conditions,
(b) above and below mean conditions, as well as
(c) the extreme years of gasoline sales.

7.3.1. Mean conditions

Compared to the other fuel blends being analyzed, there is an observation suggesting that bio-ethanol fuel production in southern African would be highest when E24 is used as the regional standard fuel blend in all conditions of market change. Swaziland, on one hand, has a significantly smaller market size for bio-ethanol fuel blends during mean quarterly (i.e. January-March months) and mean annual conditions (Figs.7.4a and 7.5a respectively). During normal quarterly (annual) conditions, the consumption of the different bio-ethanol fuel blends ranges from 75 to 150 (250-450) million gallons, where E10 records the lowest market size in South Africa (Figs 7.4b and 7.5b).

7.3.2. Above and below normal market conditions

Positive departures of gasoline sales in the region have positive influence on sales of all blends where the E24 fuel records the highest sales per unit time (Figs.7.6 and 7.7), while the opposite can be experienced during below normal quarterly and annual conditions (Figs. 7.8, 7.9). The low quarterly sales would have major economic impacts on daily production, sales and returns for the bio-ethanol fuel industry, especially when fuel blends such as E12 and E15 are used. Increased impacts of low fuel volume sales on ethanol fuel economy are largely effected by the extra costs associated with the conversion petrol engines to burn fuel blends higher than E10. Automakers do not warranty cars running on ethanol fuel blends higher than E10, a process that further limits the economic viability of lower fuel blends where engine modifications are necessary (See Chapters Two and Eight).

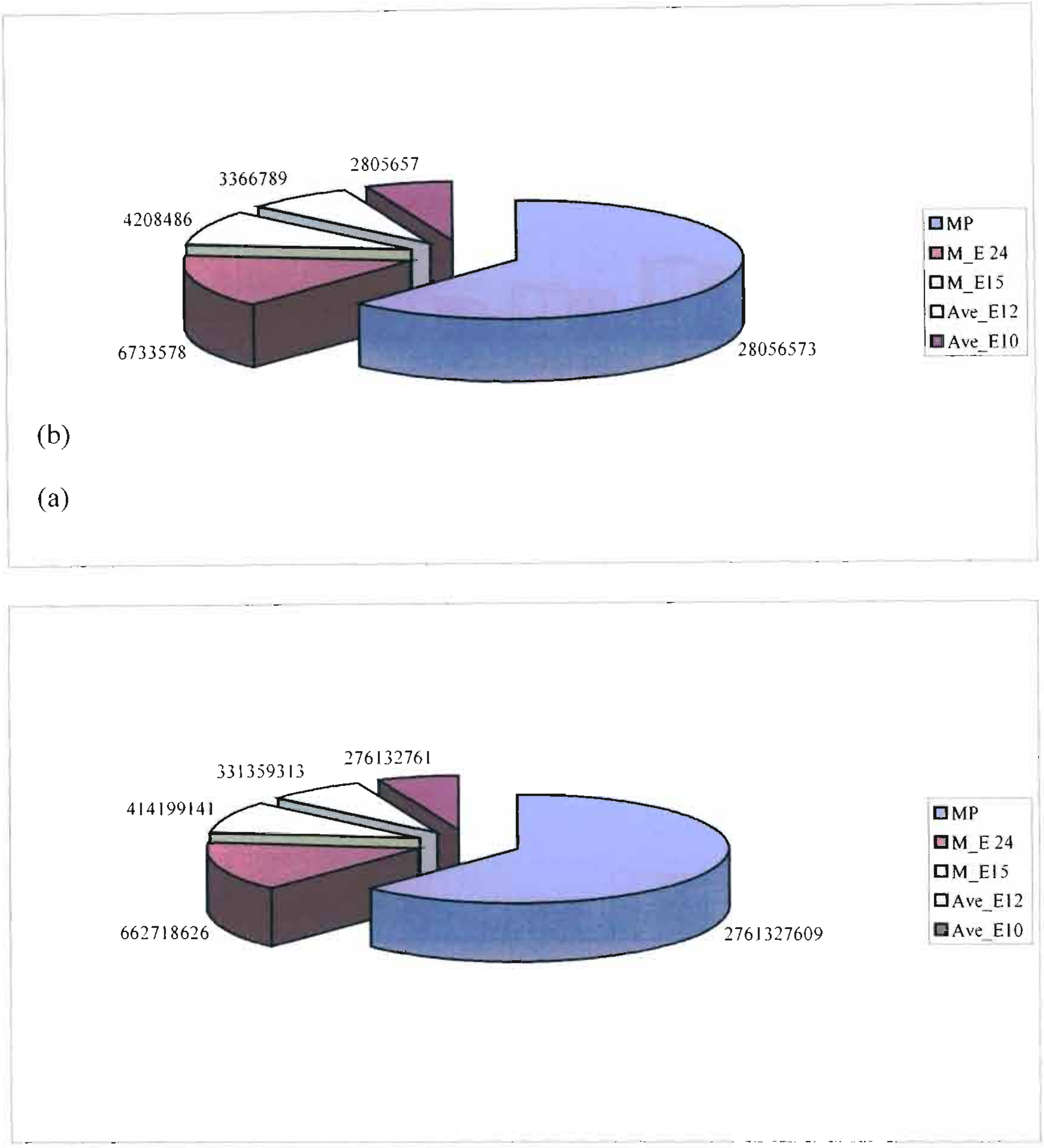


M: mean Ave: average

E24, E15, E12 and E10: percentage ethanol fuel in petrol

Q1-4: 3-month (quarters) consumption of petrol / ethanol fuel in a year

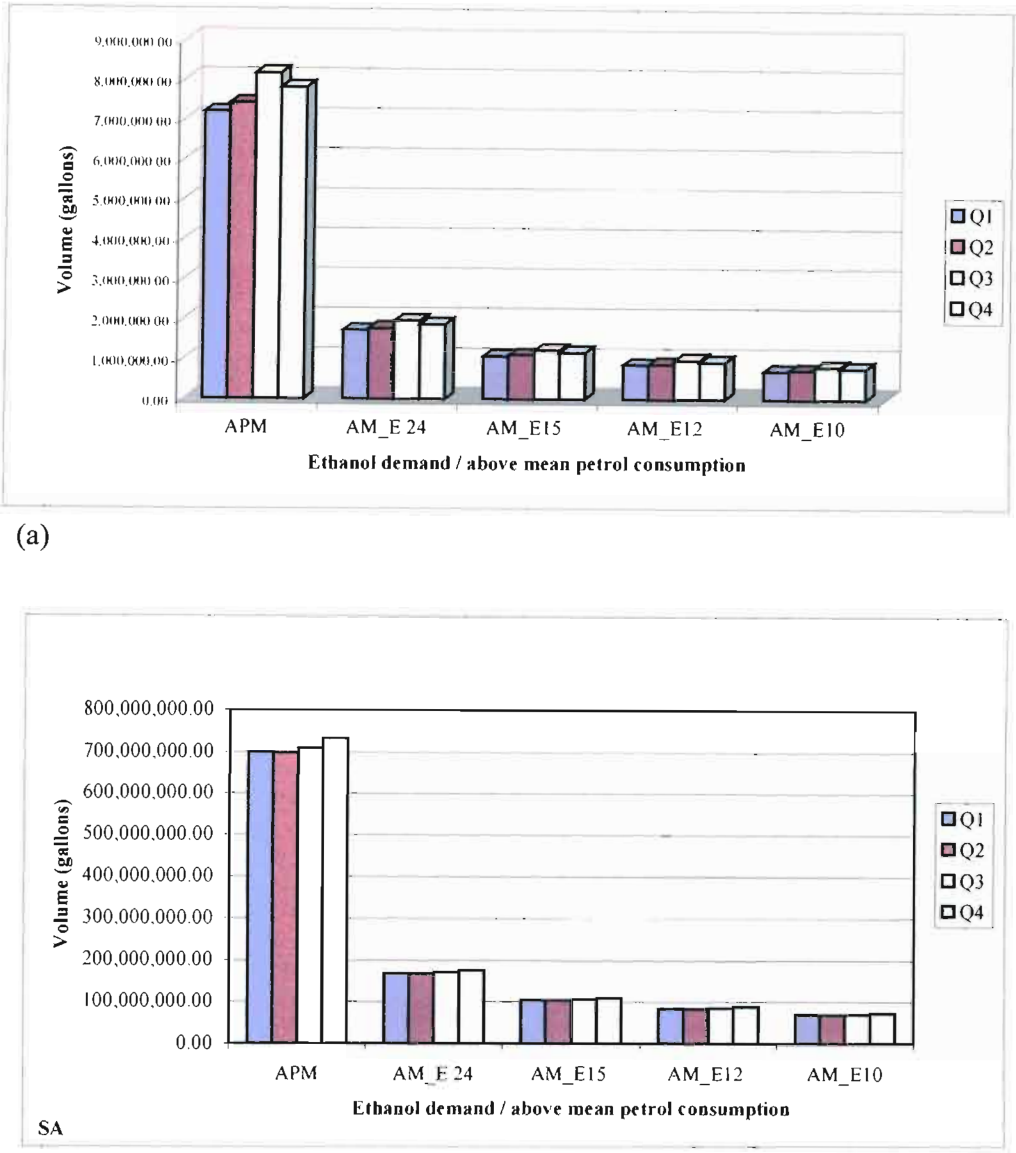
Figure 7.4: Mean ethanol conditions: quarterly average market size (a) Swaziland (b) South Africa.



MP: mean annual gasoline (petrol) consumption used to calculate ethanol demands for the different blending ratios

Ave: average of bio-ethanol percentage in gasoline (i.e. Ave_E12 = 12% bio-ethanol in gasoline)

Figure 7.5: Mean conditions: annual average market size (a) Swaziland (b) South Africa.



(a)

(b)

AMP: above mean annual gasoline (petrol) consumption used to calculate ethanol demands for the different blending ratios

AM: above mean average demand of bio-ethanol based on above average conditions of gasoline consumption

Figure 7.6: Quarterly conditions of petrol and ethanol in above normal years: average market size (a) Swaziland, (b) South Africa in the period 1995-2001 and 1994-2001 respectively.

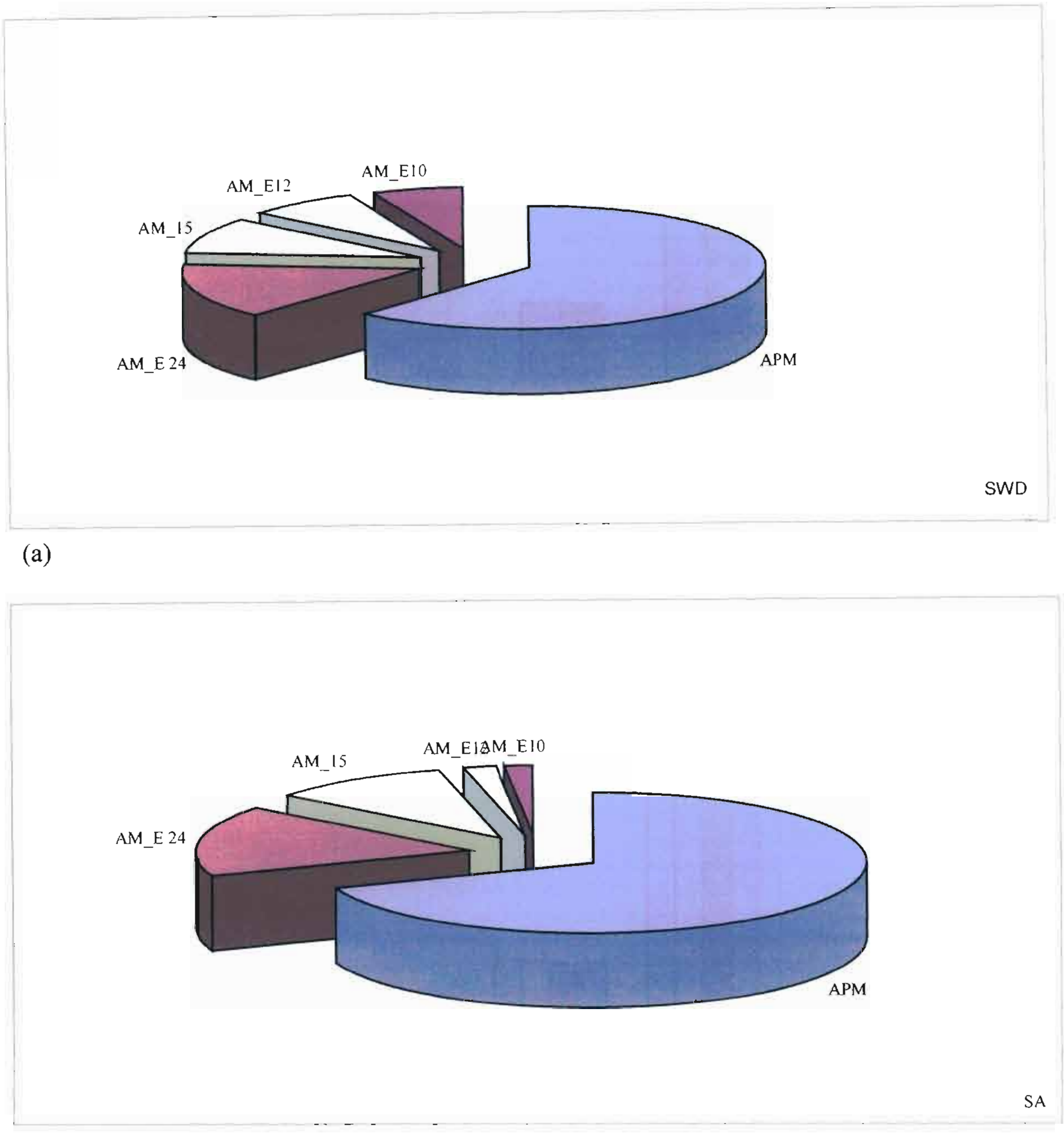
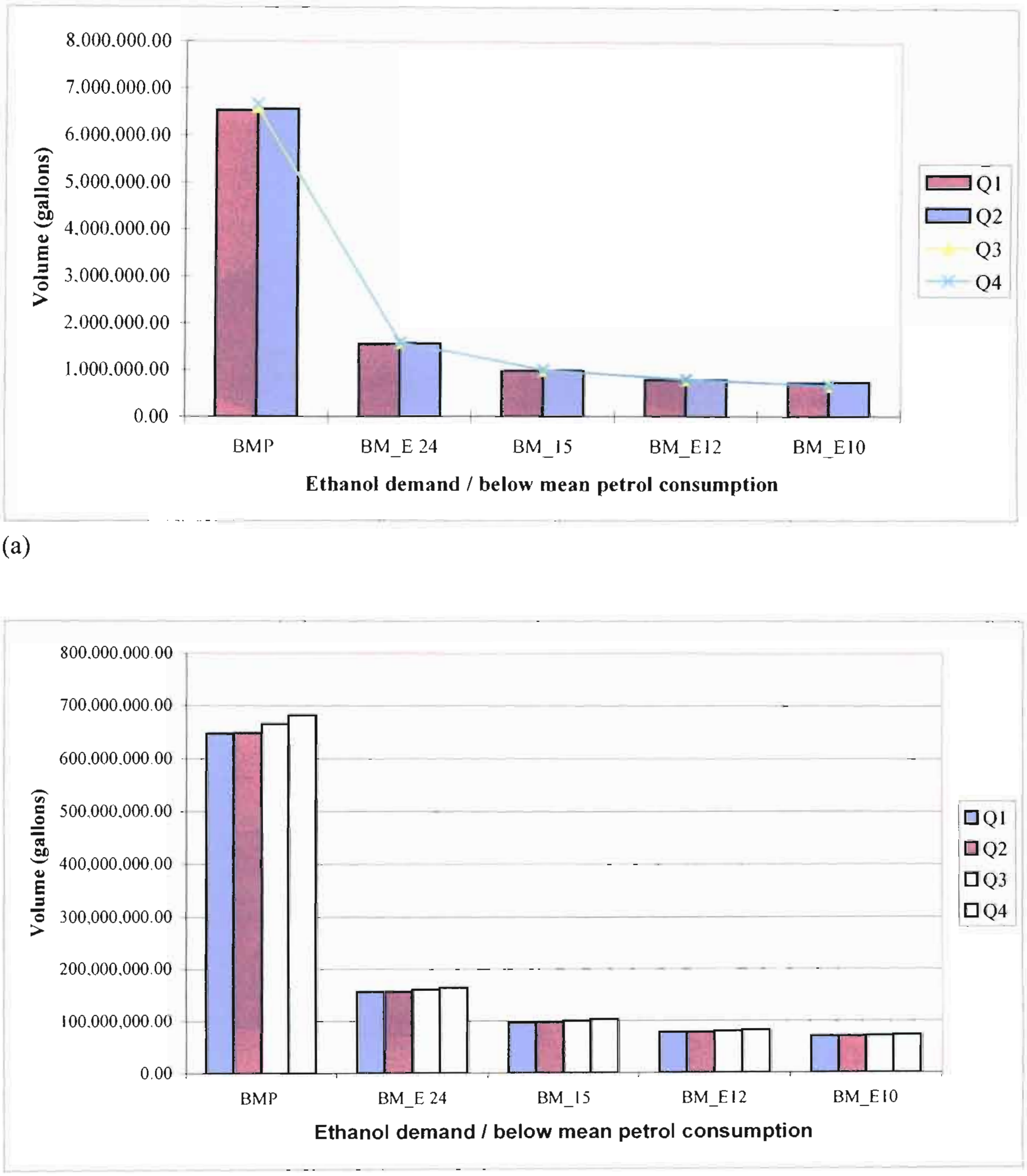


Figure 7.7: Above mean annual petrol and ethanol: average market size (a) Swaziland, (b) South Africa in the period 1995-2001 and 1994-2001 respectively.



(a)

(b)

Figure 7.8: Ethanol market conditions during below normal quarterly conditions in (a) Swaziland (b) South Africa over the period 1995-2001 and 1994-2001 respectively.

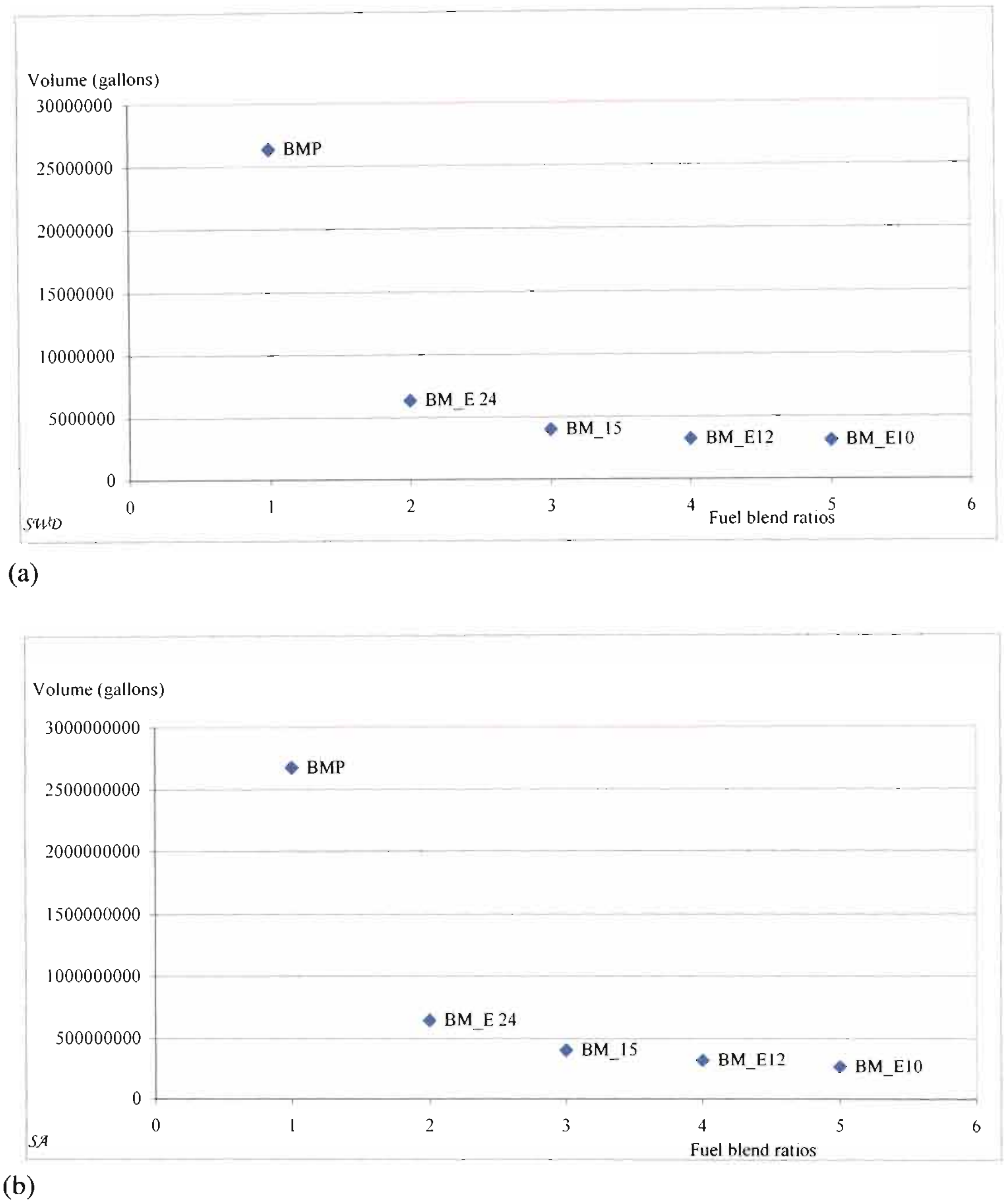


Figure 7.9: Below mean petrol and ethanol conditions: annual average market size (a) Swaziland (b) South Africa in the period 1995-2001 and 1994-2001 respectively.

7.4 Sensitivity of Ethanol Markets

While the stand-alone use of ethanol in the transport industry still remains impaired for almost all car engines currently available in the region, the size of the product market will continue to be influenced by the amount of the imported fossil fuel. Temporal, as well as spatial market variability for ethanol fuel will always follow trajectories of petrol sales in the region. The notion of blending ethanol with gasoline is not the most appropriate and viable industrial undertaking, given the unreliability of supplies, as well the volatile prices of foreign conventional gasoline. Blending ethanol with gasoline does not address the energy problems of the region, as the ethanol industry still remains tied to periodical oscillations of conventional gasoline. While afforded the possibility to create a very stable market for ethanol, as a stand-alone fuel (E100), effective exploitation of this opportunity remains an indispensable exercise for the long-term viability of bio-ethanol energy development in southern Africa. The suggested process demands greater scientific, commercial, economical, marketing, environmental, social, as well as political merits from the region as a whole. The principal goal of these process merits would be to use the highest fuel blend (i.e. the U.S.A. E85 FFV) possible within the limits of the current global auto technology. Further, fuel additives such as leaded, aromatics, MMT need to be replaced with ethanol fuel both as a fuel additive and an extender in the region.

7.5. Summary and Conclusion

The preceding two chapters demonstrated the potential for southern Africa to produce bio-ethanol fuel from sugar cane lignocellulose using bagasse and trash (leaves and leaf tops) for the transport industry. This chapter has shown the market characteristics of bio-ethanol fuel in the region. Given the observed market characteristics of bio-ethanol fuel in southern Africa, there is now evidence to suggest that not all sub-regions producing sugar cane can develop ethanol plants based on lignocellulose as the only feedstock. Supplementary sources (e.g. sweet sorghum, municipal waste, newspapers, switchgrass and wood waste) would have to be developed to meet the economically viable plants sizes. Further, the analysis given in this chapter has shown that sales of bio-ethanol fuel blends directly respond to petrol sales in the region. Blending with petrol fuel would therefore directly link bio-ethanol sales to increased ethanol price volatility in fashions characterizing petrol prices all over the world. The process would increase the sensitivity of the bio-ethanol industry, because:

(a) international petrol price volatility would directly make bio-ethanol prices highly volatile in the region,

(b) the amount of petrol consumed in the region would directly influence the market size for bio-ethanol fuel (i.e. increased volume sales of petrol would improve bio-ethanol sales, while the opposite would occur with reduced petrol sales per unit time),

(c) the economic viability of bio-ethanol production for blending with petrol is directly dependent on the economy of conventional petrol, irrespective of the availability of government price control and market regulation structures, and finally

(d) considering items (a), (b) and (c), international producers of conventional petrol can use this direct dependence of ethanol fuel to regulate (or control) the growth and development of the industry in southern Africa, a process that undermines regional efforts to improve energy security and human development in all parts of the subcontinent.

Although the work undertaken to this far has managed to link lignocellulosic bio-ethanol production potentials with fuel economics and markets, the integrated approach in analyzing the industry described in Chapter Four is still not yet achieved. The remaining task is now to link these three processes with human development per capita and land (environmental) stock limitations. In the process, the hypothesis that developing bio-ethanol fuel on the basis of agricultural intensification is not sustainable, given the infinite upper limit for development consumption per capita, can be tested at the sub-regional scale as demonstrated in the next chapter.

Chapter Eight

Bio-Ethanol Fuel Production for Human Growth and Development

8.0 Introduction

Discussions given in previous chapters have shown the production, business, and market potentials for intensive development of biomass ethanol fuel. The issue that still needs clarification is whether agricultural intensification can affect land stock potentials for bio-ethanol fuel production over time. In recent years, the amount of work linking the decline of land stock potentials with long-term agricultural intensification has been increasing (Meyer *et al.*, 1996; Van Antwerpen *et al.*, 2001). Hence, demonstrating the possible implications of developing bio-ethanol fuel on the basis of agricultural intensification for land stock potentials is important in this chapter. The process is achieved by showing the relationship between biofuel (bio-diesel and bio-ethanol) production, market development, and human population growth as well. The analysis is undertaken at the sub-regional scale (Swaziland).

8.1. Limitations for Human Growth and Development

Over the last few decades, substantial progress has been made in the field of ecological economics in understanding that dependable supplies of natural capital and its derived goods are the basis for efficient economic development (Berkes and Folke, 1991). However, according to Berkes and Folke, the limitations of the physical environment constrain growth and development of human subsystems. In the process, human subsystems actively modify natural land potentials, allowing effective human adaptation to limitations of the physical environment over time (Mitsch and Jogensen, 1989). While ignoring the spatial inequalities, the general growth in global economics may demonstrate the success of human adaptation to constraining natural stock consumption limits, as portrayed by Simon (1994). In the process of successful remodeling, Hall (1996) stated that humanity has exceeded the limits of natural life-supporting systems to the point of creating critical supplies of the basic resources that define and sustain human existence. This observation confirms the assertion that human subsystems can switch the earth's science system to alternative modes of operation that are irreversible (The Global Environmental Change Programmes, 2001).

In closing the gap between production, business and markets, the implications of biofuel development for land stock limitations in Swaziland are demonstrated in this chapter. The analysis of human-environmental relationship presented in this chapter critically considers the arguments given by Bartlett (1994; 1997-1998), Costanza (1994), Ehrlich (1994), Pimentel (1994), Tainter (1996), United Nations (2002) and many others. The reflection of this investigation embraces the assertion made by Durham and Fandrem (1988) that the disjunction market surpluses of food and worldwide nutritional shortfalls appear to be symptomatic of the underlying world's susceptibility, raising questions about the sustainability of agricultural intensification. How is it possible that because of advances in agriculture in developed countries, the world experiences substantial surplus of food (Abelson, 1987), while at the same time more people than ever before are undernourished (Chandler, 1985; Wortman, 1980). Although there is basis for challenging the simplistic narratives of the physical environmental change associated with human subsystems by Mortimore (1989), Warren (1996) and others, Daly and Townsend (1993) highlighted that it remains impossible for the world's economy to grow its way out of poverty and irreversible environmental change (i.e. sustainable growth is impossible).

Bio-ethanol fuel development may be the solution to the current shortfalls in global (a) supplies of transport fuel, (b) creation of dependable local markets for agriculture, and (c) non-functional rural economies. However, developing biofuels using the rhetorical principles of sustainable growth and development characterized by major limitations discredits the intended purpose and benefits of this important undertaking. It further makes bio-ethanol fuel development a highly debated industry, with such magnitude of attention it receives from politicians, economists and technocrats all over the world. Hence, the need to assess the implications of biofuel development for land stock potentials in Swaziland has been identified on the basis of fuel demand per capita in a changing human population size. Achieving this process is a function of four contrasting parameters:

(a) increasing energy demand against declining natural energy supply systems,
(b) increasing human numbers against dwindling supplies of basic natural land stock,
(c) demand for sustainable human development against increased consumption per capita, where most of the country's people lack dependable food supply and access to clean energy, and
(d) the need for sustaining dwindling supplies of land stock against the growing demand for increased human consumption, therefore allowing sustainable economic growth to exist.

The analysis given in this chapter identifies four critical challenges for the biofuel industry. These challenges are:

(a) increasing biofuel markets,
(b) increasing demand for land stock,
(c) optimizing land stock potentials, and
(d) sustainable growth and development.

The discussion given herein identifies environmental implications of using biofuels in the transport industry. The process is achieved by demonstrating the effect of increasing biofuel consumption per capita in either a constant or growing human population size. Firstly, the base demand for bio-ethanol fuel and bio-diesel is demonstrated using the current consumption rates of gasoline and diesel per capita and population size in Swaziland. A highlight of the impacts of biofuel production on land stock for a developing and growing size of human population then follows. Based on historical records of sugar cane production in Swaziland, the relationship between intensifying feedstock production, land potentials and biofuel production is indicated. Using simplified illustrations, attempts to understand the effect of intensive land stock consumption on biofuel production over time have been made in this chapter. On the basis of the findings drawn from the above processes, the relevance of sustainability to biofuel production in an environment characterized by increased human development and population growth is also established. The necessary tradeoffs for successful bio-ethanol development in Swaziland are presented last in this chapter.

8.2. Biofuel Demand

In so many ways, connections between the various subsystems of the earth, suggested by The Global Environmental Change Programmes (2001), extremely complicate the efficiency of biofuel consumption in developing too many people. While the world's human population of nearly 6-7 billion (http://www.census.gov/cgi-bin/ipc/idrank.pl), consumed in excess of 75million oil barrels per day by the end of 2001, with about 3.3% of the oil consumed by Africa's population (of nearly 800 million) (BP, 2002). During the same year, the daily oil consumption was 19.6 million barrels in the U.S.A (i.e. a developed country with a population of nearly 285 million (a little > 1/3 of Africa's human population)), which fell significantly low in Africa (about 2.5 million barrels) as a whole, BP indicated. Using the oil consumption records provided by BP (2002), South Africa, with a population of just over 44 million (http://www.census.gov/cgi-bin/ipc/idrank.pl), consumed about 488 thousand barrels of oil per day. The daily oil consumption per capita was about 0.07 barrels in the U.S.A., decreasing to about 0.01 barrels in South Africa.

Historical records of gasoline and middle distillates show that Swaziland consumes an annual average of 200-250 million litres. Given the human population size of nearly 1 million, Swaziland's average daily total consumption per capita is about 0.548-0.685 litres (nearly 0.13 U.S. gallons or 0.0031 U.S. barrels). Based on the increased daily consumption rate of gasoline and middle distillates per capita in developed countries (i.e. 0.0517 barrels in the U.S.A.), equitable human development in South Africa and Swaziland identifies the need to increase fuel consumption per capita by at least 5 and 17 times in these countries respectively. The indicated daily fuel consumption rates per capita in developed countries (i.e. in the U.S.A.) is certainly not the upper limit, a factor that requires critical consideration in developing bio-ethanol fuel for the transport in Swaziland. With the understanding that Swaziland has no oil and natural gas reserves, increasing the daily transport fuel consumption per capita by 18 folds in the country through bio-ethanol and bio-diesel production will have major implications for the natural environment.

8.2.1 Human population growth

Swaziland's human population size in 2004 has been estimated at 1,169,241 (http://census.gov/cgi-bin/ipc/idbrank.pl). However, the base population size of 1 million is used in this investigation. Although the national population growth rate is nearly 2.1-3% per annum, a conservative annual growth rate of 2% for nearly half the years where population growth occurs. For years not indicated in Fig. 8.1, population growth is negligible. This has been done to generally balance population declines effected by diseases such as AIDS. Based on the afore-stated notions, a significant population growth over a period of 18 years where in nearly half of the period population growth per annum is considered zero can be expected in Swaziland (Fig. 8.1). Asserting that each person competitively develops over this 18-year period (i.e. transport fuel consumption per capita becomes competitive with the first world countries (e.g. U.S.A.)), Swaziland offers an important potential market for biofuels.

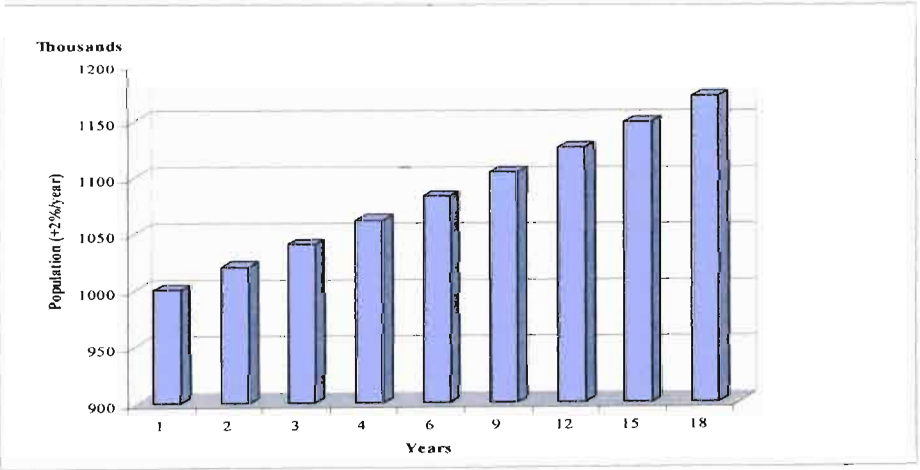


Figure 8.1: Projections of human population change in Swaziland over an 18-year period.

8.2.2. Development, population growth and biofuel demands

Development means increasing human consumption of resources (Daly and Townsend, 1993; Pimentel 1994; Pimentel *el al.*, 1996; Rees 1996). Generally, it is common that rich people constantly shift concerns of population problems to the poor characterized by significantly lower consumption per capita (Ehrlich, 1994). Although rich people in Swaziland account for nearly all gasoline and diesel consumed, development per capita (i.e. fuel consumption by the poor and the rich) increases the demand for biofuel production over time (18-year period considered here) (Fig. 8.2). Given the base consumption of nearly 0.0164 l/day of bio-diesel fuel, when using a fuel blend of 5vol% in 95vol% conventional diesel, human development would increase bio-diesel consumption per capita to nearly 0.3 l/day over 18 years on one hand (Fig. 8.2a). Further illustrated in Figure 8.2a is that bio-ethanol fuel consumption would increase from about 0.0329 l/day per capita to nearly 0.6 l/day (i.e. using a blending ratio of 10vol% bio-ethanol in 90vol% gasoline) over the same number of years. The annual consumption of biofuels (bio-ethanol and bio-diesel) per capita increases from the 0.0493 l/day to nearly 0.9 litres per day per capita (Fig. 8.2a). Over twelve months, the consumption rate of biofuels would increase from the current estimate of about 18 litres to 330 litres per capita (Fig.8.2b).

In fashions similar to those observed above, the national bio-ethanol fuel (bio-diesel) consumption increases over the 18-year period. Assuming that the population size remains constant for the 18-year period (i.e. deaths balance births), the daily biofuel consumption by the nearly 1 million population would be about 900 thousand litres at the end of the period (Fig. 8.3a). The blending ratio of 5vol% bio-diesel in 95vol% diesel leads to a significantly low consumption rate of about 300 thousand litres per day at the national scale. Over 300 million litres of biofuels would be consumed by a developing population of 1 million during the 18th year at the consumption rate of 0.9 litres per day (Fig.8.3b). It is important to understand that the amount of bio-ethanol used in producing bio-diesel (during transesterification) has not been considered in this analysis, which would take about 10vol% of oil used (bio-diesel produced).

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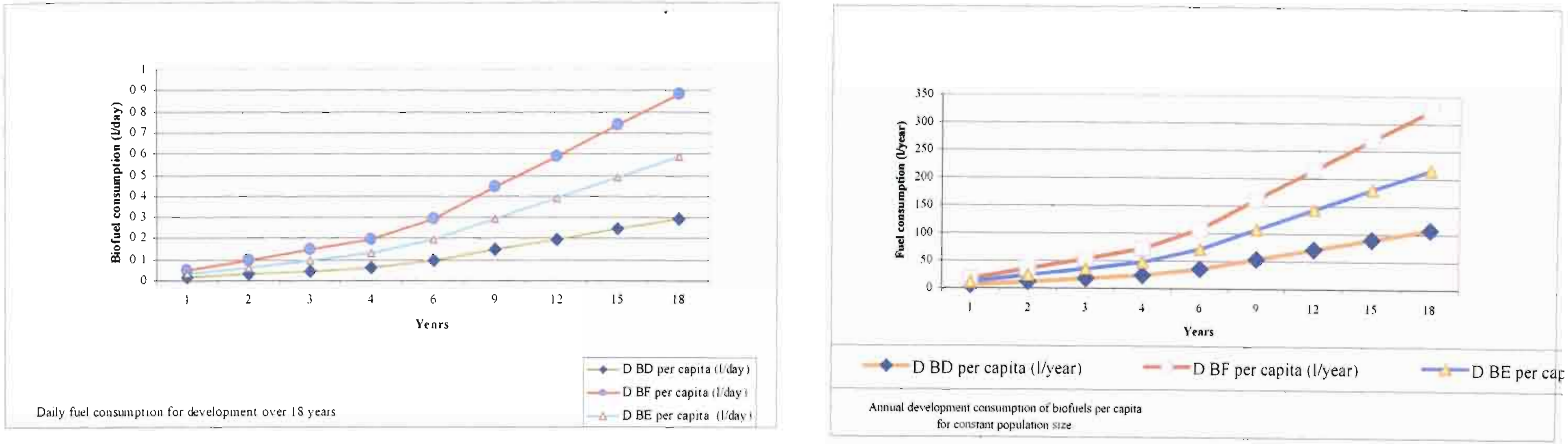
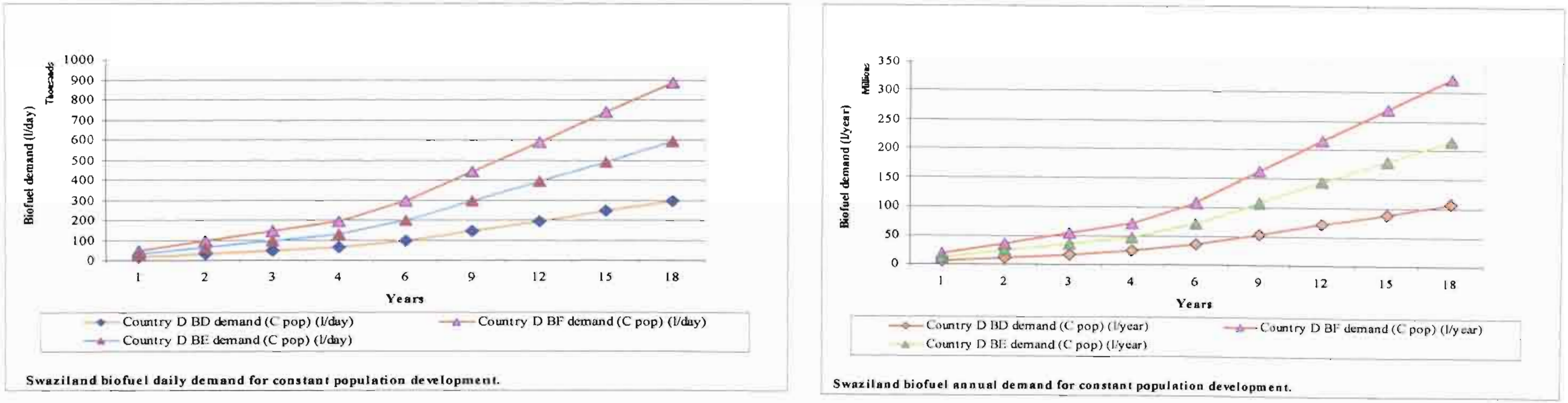


(a) (b)

Figure 8.2: Influence of development on (a) daily, (b) annual biofuel demand per capita. D: development; BD: bio-diesel; BE: bio-ethanol; BF: BD+BE



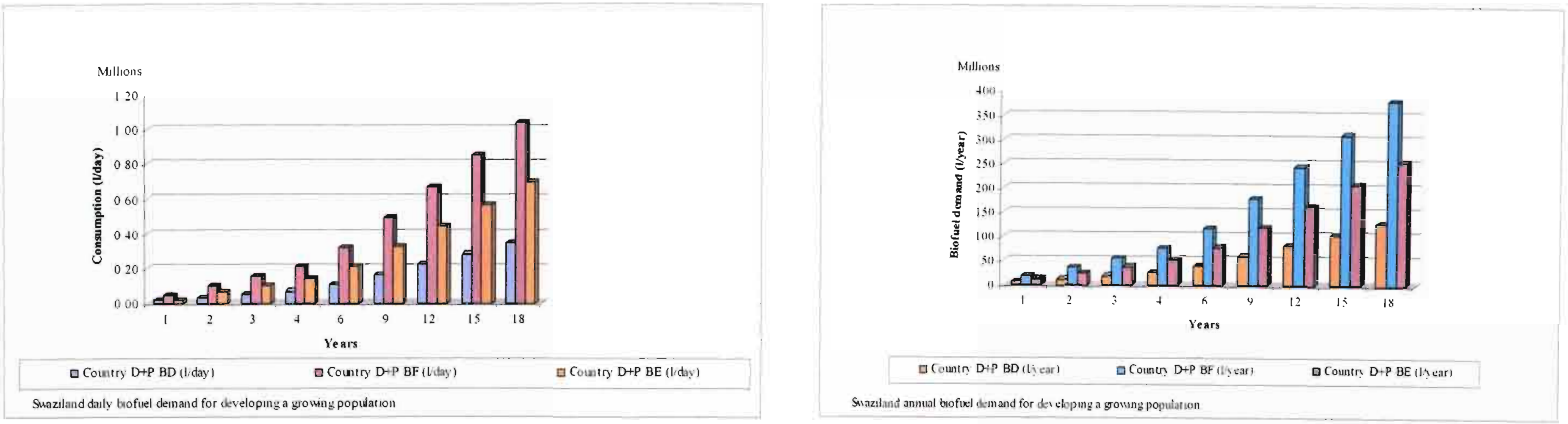
(c) (d)

Figure 8.3: Effect of developing a constant population size on (a) daily, (b) annual biofuel demand in Swaziland. D: development; BD: bio-diesel; BE: bio-ethanol; BF: BD+BE

Development per capita and population growth significantly increase the daily and annual demands for biofuels in the country (Fig.8.4). Developing a growing population size would increase the daily consumption rate of biofuels in Swaziland from nearly 50 thousand litres per day to over a million litres per day during the eighth year (Fig.8.4a), with an annual total consumption ranging between 350 and 400 million litres (Fig. 8.4b). Using blending ratios of bio-diesel (5vol%) and bio-ethanol (10vol%) with the respective conventional fuels differentially influence the demand for land stock in the country.

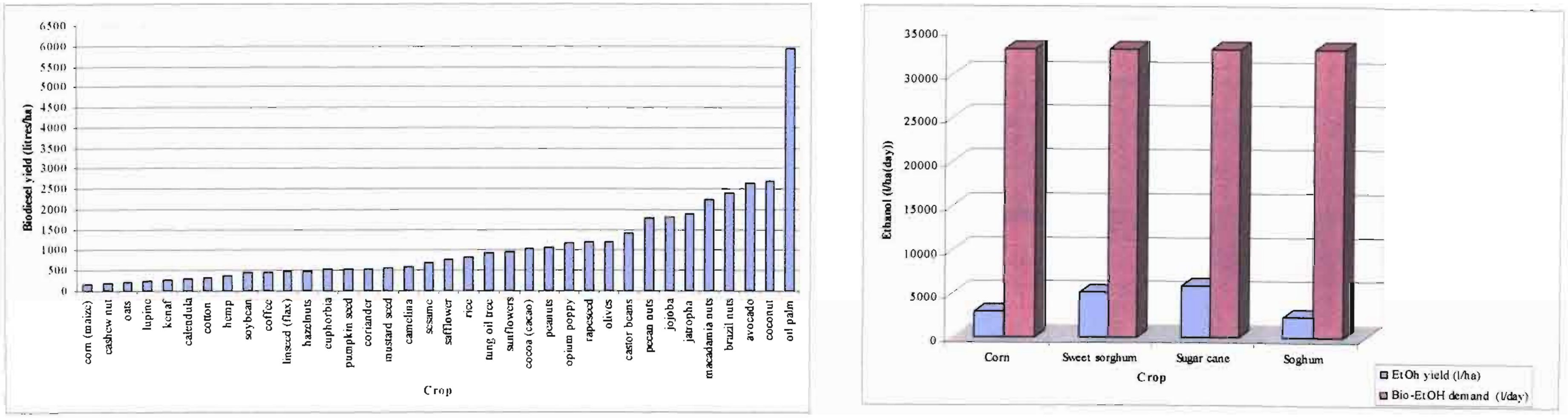
8.3. Effect of Biofuel Production on Land Stock Demand

The land demand for biofuel production would depend on the crop, as well as the land stock potentials, assuming that all other factors influencing land-crop performance are optimal. Based on this assumption, Figure 8.5 illustrates the variation of bio-ethanol production potentials per unit area for different crops. Over 400 hectares of land would be required on daily basis to produce biofuels for a developing and growing population of nearly 1.2 million in the 18th year (Fig. 8.6a). This adds up to nearly 150 thousand hectares per annum (Fig. 8.6b). The choice of feedstock is critical for efficient management of land stock demand and consumption. Sweet sorghum has a significantly reduced demand for land stock than sugar cane and corn per annum (see Chapter Three).



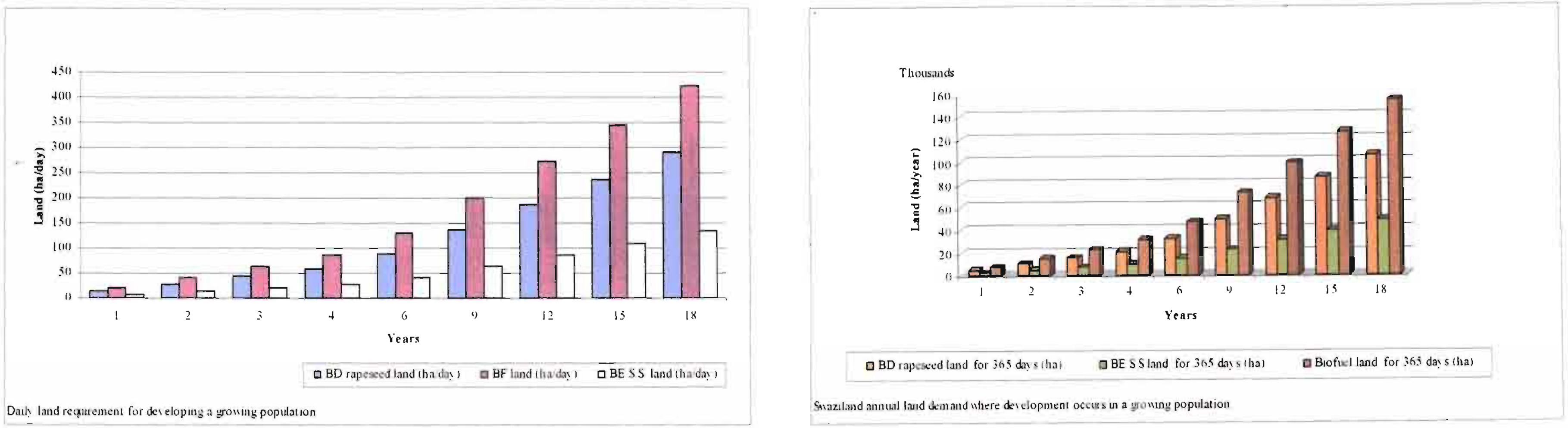
(a) (b)

Figure 8.4: Biofuel (BD: bio-diesel, BE: bio-ethanol) demand for developing (D) a growing population (P) per (a) day, (b) year.



(a) (b)

Figure 8.5: Feedstock potentials for (a) bio-diesel, (b) bio-ethanol (Bio-EtOH) production.
Source: (a): http://www.journeytoforever.org/biodiesel_yield.html



(a) (b)

Figure 8.6: The land requirement for (a) bio-diesel (BD) and bio-ethanol (BE), (b) biofuel (i.e. total land required for bio-diesel and bio-ethanol) production.

8.4. Land Stock Limitations for Bio-Ethanol Fuel Development

The highlight given in preceding sections has identified the core challenges for developing biofuels. More often ignored on the basis of increased technological innovations, improvement in crop varieties and development of new chemical fertilizers (see Boserup, 1965; 1993; Costanza, 1994) are the defined limitations of natural land stock to human consumption (Durham and Fandrem, 1988). Science and technology are very important in achieving efficient management and increasing outputs of various land resources, but these processes cannot increase the flow of natural land resources available for exploitation, suggested Pimentel (1994). The defined land stock potentials creating the complexity of investing on biofuel development (i.e. economics, markets, environment and population consumption) demand special attention in this investigation as a whole. The observation follows the assertion by Tainter (1996) that in many sectors of investment (e.g. resource production, technology competition, and research), complexity is increased by the continuous need to solve problems associated with the unyielding limitations of natural land stock (see next section).

8.4.1 Critical limits of agricultural intensification

Suggestions that intensive land stock consumption can influence better management of the environment (Binns, 1997, Boserup, 1965; 1993; Satterthwaite, 1997; Tiffen *et al.*, 1994) are now challenged by the accumulation of new evidence suggesting the opposite (Durham and Fandrem, 1988; Pimentel *et al.*, 1996; Qwabe, 1997). These challenges are on the basis that using the myopic laws of economics implying that shortage of product supply, in a growing population instil greater production and economic growth (Simon, 1982; 1983; 1991; 1994), leads not only to declines in land stock natural abilities, but also to increased costs toward meeting the expectations of these economic laws. Increased material production and economic growth through agricultural intensification are the serious threats to cost-effective human consumption and adaptation during phases of short supplies in natural stocks. These processes therefore create irreversible critical limitations to economic growth and development where human numbers grow irrationally. Intensifying sugar cane production in Swaziland, for example, is faced with the challenges of declining yields per unit area, dwindling net profits, volatile markets because of increased horizontal cane production, increased consumption per capita and declining supplies of new land stock, among other factors. There are instances where intensive cane production competes with other developmental processes for dwindling supplies of fixed natural stock. On the basis of the discussion presented above, it can be argued that intensive land stock consumption (e.g. in the form of agricultural intensification) links all agents of critical environmental quality and non-sustainable potentials and capabilities of natural land stock.

Humanity exists to maximally consume natural stock and not to grow or develop it. The economic drive of agricultural businesses is maximizing returns from low investments. However, the general observation in the Swaziland sugar cane industry, as well as in other parts of the world is that continuous intensive crop production leads to significant declines in land stock potentials over time, and further limits the long-term viability of agricultural businesses (Fig. 8.8) (see also Durham and Fandrem, 1988). During the first few crops (1963/64 –1967/68), cane yields per unit area at Mhlume Sugar Mill were the highest in all years of mill's existence (Fig.8.8). Various factors may have contributed to these extremely high yields, which include (a) cane production was limited to the best soils in the area, (b) very high quality of virgin lands, (c) low horizontal cane coverage allowed efficient crop management, (d) lack of accumulation of chemical fertilizers that degrade soil quality more often associated with intensive monocropping, and (e) abundant water supply even during an excessively dry year of 1965 (Qwabe, 1999). The statement made by Tainter (1996) that the history of cultural complexity is the history of human problem solving, becomes more relevant when crop yields per unit of land decline over time. These declines in land potentials (i.e. land crop values) are more often countered by increasing investment per land unit, as well as advancements in technological efficiency and management practices (Fig. 8.8).

Human adaptation generally follows the suggestion that as more easier solutions are exhausted, problem solving moves inexorably to greater complexity, higher costs, while returns on investment diminish significantly (Tainter, 1996). According to Tainter, declines in profits may not necessarily lead to the collapse of land stock

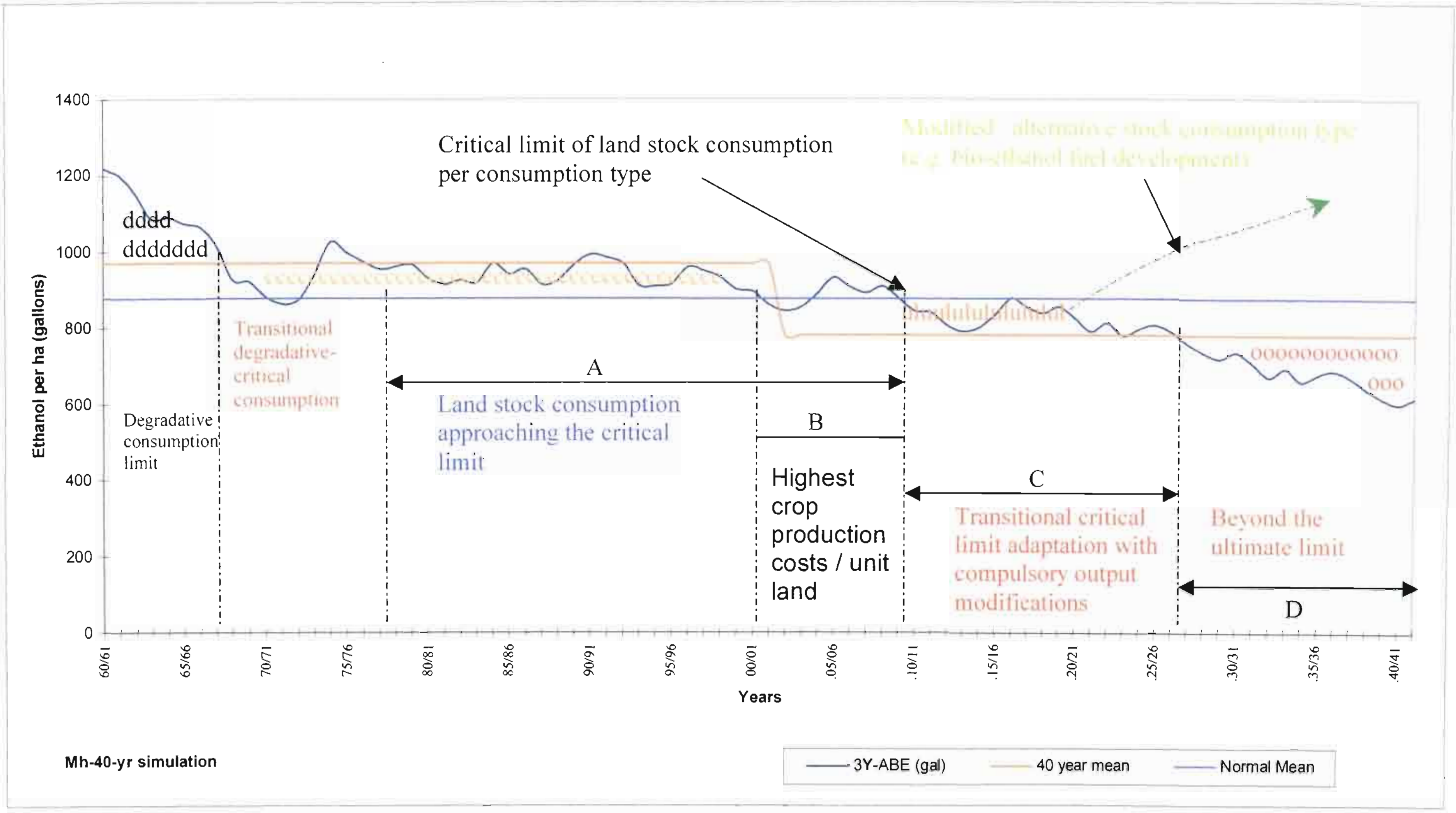


Figure 8.7: Industry adaptation to differential limits of sugar cane feedstock production per hectare in the period 1963/64-2042 (at Mhlume Sugar Mill).

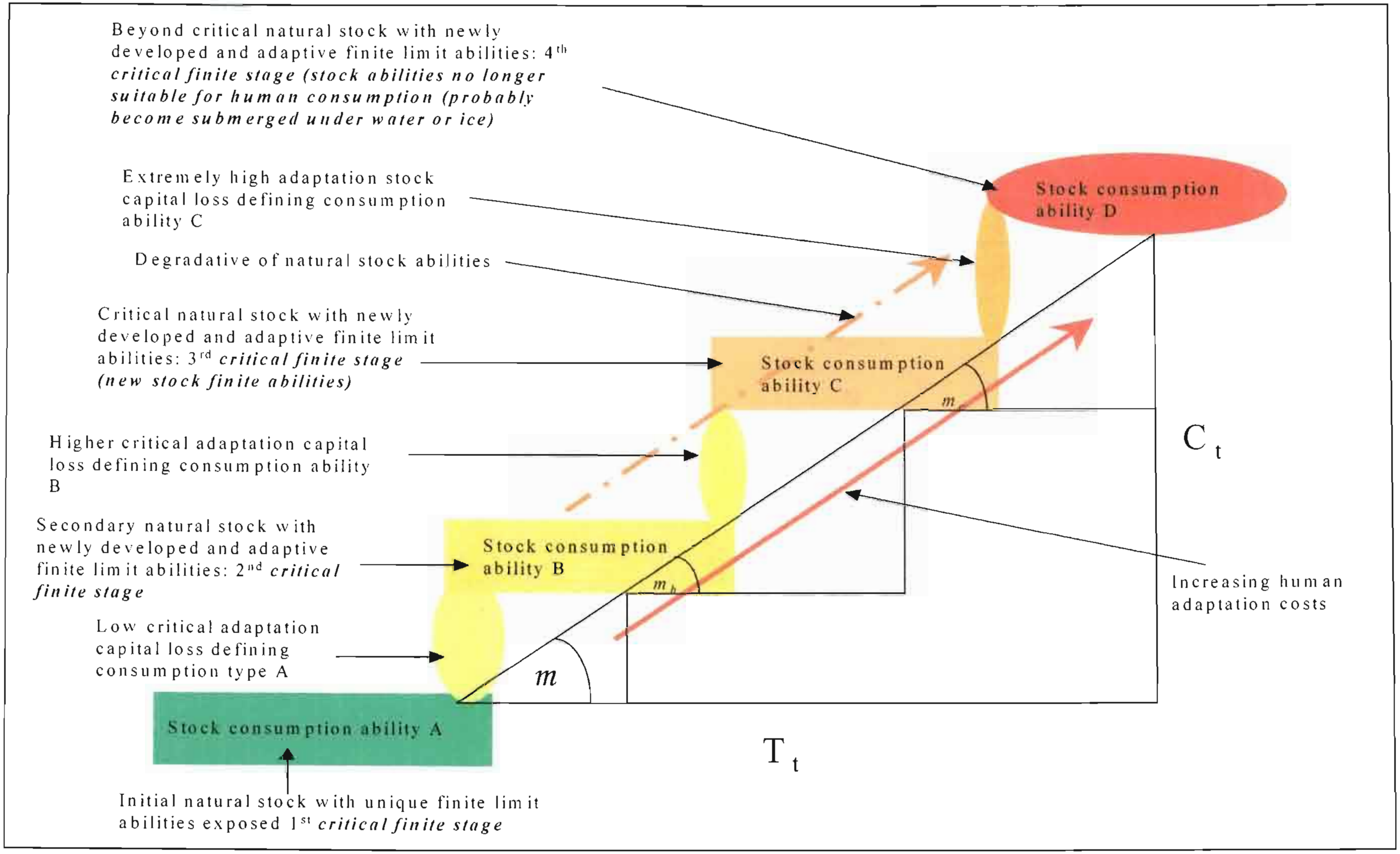


Figure 8.8: Natural stages of land stock adaptation to critical human consumption. T_t is the total time taken by the stock to assume new finite abilities from stage A-D. C_t refers to the total capital loss by the stock from the finite abilities of stage A-D. *m* is the total consumption capital.

Human Adaptation Cycle to Limitations

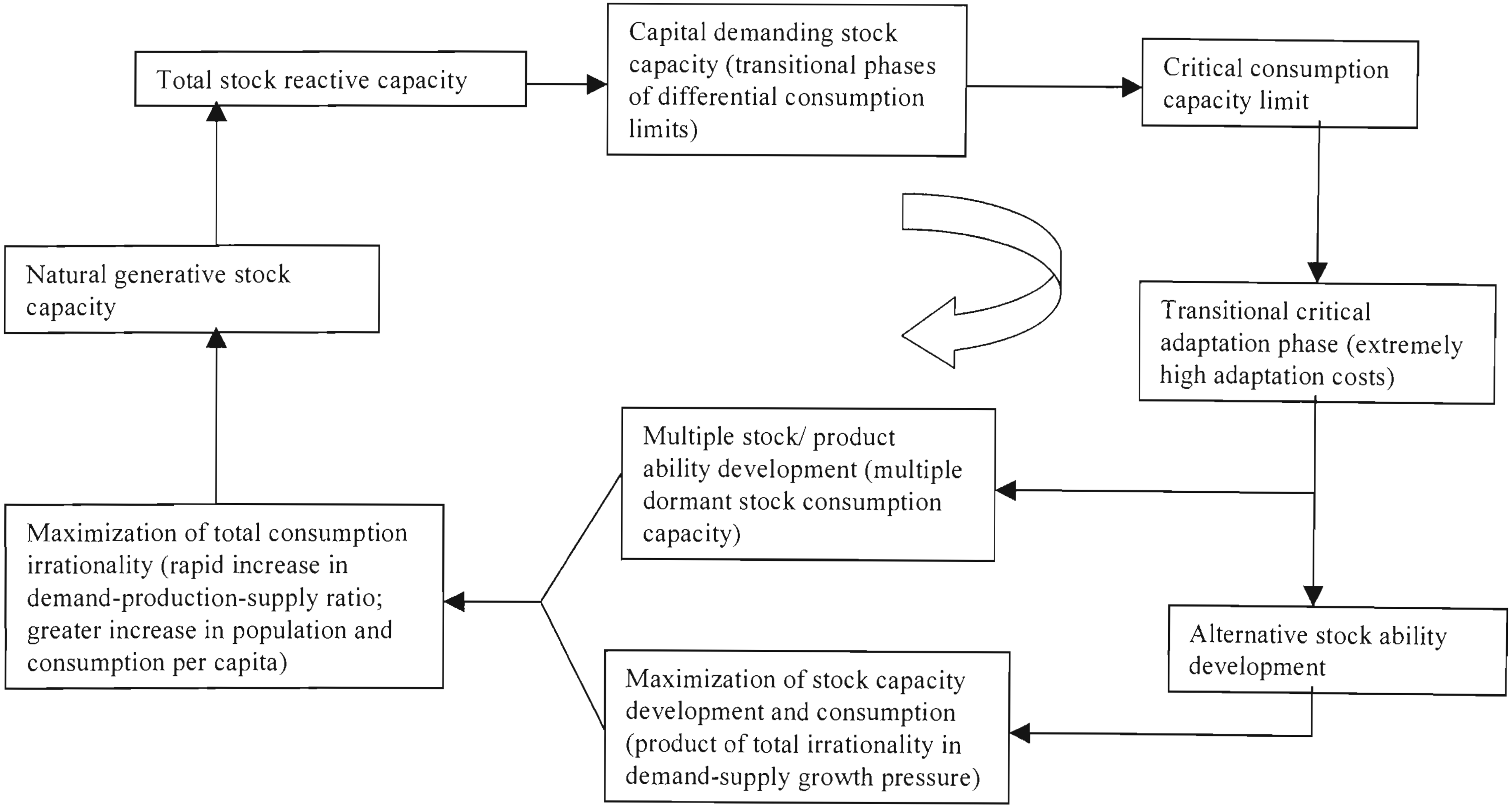


Figure 8.9: Human adaptation process to consumption limits of natural stock.

consumption, but the costs of adapting to these changes are significantly high. Figure 8.7 illustrates that the idea of producing bio- ethanol fuel from cane lignocellulose is another adaptation process to the increased cane production and management costs, reduced land potentials and greater declines of returns on investments. Using bio-ethanol fuel production in Swaziland based on the analysis given in Section 8.1 and 8.2, a cyclical process of human adaptation to land stock limitations is identified in this work (Fig.8.9). This process explains the relationship between land stock potentials, intensive consumption of land stock potentials, as well as the process of human adaptation to land stock limitations.

8.4.2. Conditions beyond the critical limit

Contemporary science is humanity's greatest exercise in problem solving (Tainter, 1996). According to Preiser (1994), technological progress undoubtedly leads to efficiency improvements, resource substitutions, as well as better adaptation to critical conditions of natural stock per unit of time (illustrated in Fig. 8.8 and 8.9). In the process, the costs of planning human adaptation and development on the basis of incorrect assumptions are much higher with overestimates of such rates than with underestimates (Costanza, 1989). Hence, technological advancements and spatial flows of materials create infinite levels (stages) of land stock consumption, which are defined by unique adaptation cost estimates (Figs. 8.8). Characteristics of these stages uniquely limit the flow of resource materials for human consumption. More so, the success of human consumption at each level of land stock consumption is dependent on the efficiency of technology and trade (or human adaptation process to specific limitations of land stock). Based on this assertion, conventional wisdom suggests that because technology and trade can provide infinite consumption possibilities at the various limitation stages of land stock (illustrated in Figs. 8.8 and 8.9), human carrying capacity is infinitely expandable, Rees (1996) observed. Rees further stated that there is no logic in asserting that the human carrying capacity is irrelevant to demographic management and development planning within each land stock limitation stage, when the ecological carrying capacity remains the fundamental basis for demographic accounting.

The picture painted by Simon (1994) is that processes leading to critical environments cannot hinder human development. This claim contradicts the general belief by the neo-Malthusians that increased human population and development create critical limits of land stock (see Pimentel *et al.*, 1996; Preiser, 1994). Further intensive consumption of critical stock leads to the development of conditions beyond the critical limit. The bottom line of greater consumption of critical land stock is that the laws of thermodynamics inevitably limit human consumption, if shortages of inputs or ecological collapse do not intervene first (Fremlin, 1964; Preiser, 1994). It is common knowledge that increasing investment on the development of new consumption opportunities diverts the possibility of a collapse. The development and use of biofuels in the transport industry, for example, counter the social, political, economical and environmental limitations of fossil fuels, therefore providing a clear understanding of processes characterizing the beyond critical limit (see Figs.8.7 and 8.9).

Human adaptation during beyond the critical limit of fossil fuel consumption can be explained using two distinct concepts. Except for the Middle East, the two concepts effectively explain the diversion of a possible collapse of the transport fuel industry worldwide, particularly in fossil oil deficit countries such as Brazil and the U.S.A with high consumption rates per capita. These concepts are henceforth referred to as (a) multiple stock ability development, (b) alternative stock ability development (Fig. 8.9). There is a general observation that these two concepts more often characterize the consumption of non-renewable resources, such as fossil fuels and agricultural land, which are analogous to inventories where any use implies liquidating part of the stock (Costanza, and Daly, 1992; Rees, 1995; 1996). Presented below is a description of the two concepts.

8.4.2.1. Multiple stock ability development

Based on the historical explanations of the human-nature debate, humanity has demonstrated the ability to evade or adapt to beyond critical limits of natural stock. Humanity has demonstrated this ability through developing multiple product outputs from a single (near collapse) consumption type, while improving returns on capital investment. In the sugar industry, for example, this undertaking would involve the development of (a) downstream products, (b) cogeneration, (c) production of polyols, as well as (d) the fermentation of ethanol from both five and six carbon sugars. This process is illustrated in Figures.8.7 and 8.9.

8.4.2.2. Alternative stock ability development

Developing alternative stock abilities remains the key process for successful human adaptation to stock consumption inefficiencies and limitations. Simply stated, complex consumption of land stock is a problem-solving strategy that emerges under conditions of compelling need or perceived benefit (Tainter, 1996). There is a repeated failure of human adaptation to land stock limitations over time, demanding new innovations at greater costs (see Figs. 8.8 and 8.9). This non-sustainability of consumption per stock type defines an unyielding and indispensable price that humanity has to pay in the process of adaptation. The price tends to increase with the flow of time, particularly upon completion of each human adaptation cycle consisting of differential stages (Figs. 8.8 and 8.9). The difference between sustainability and non-sustainability becomes clear when non-renewable resources form the basis for human development. Developing electric cars, fuel cells and biofuels, as substitutes to fossil fuels, for example, defines the alternative process characterizing the stage beyond the critical point (refer to Figs. 87 and 8.9).

The effect of human load on the creation of beyond critical conditions of land stock is not a function of naturally regulated population numbers, but a dependent of human consumption rates per capita beyond the survival consumption limit (refer to Sections 8.1 and 8.2). According to Rees (1994), the influence of developmental consumption per capita on the creation of critical and beyond critical conditions of land stock is increasing more rapidly, because of the expanding trade and technology. Trade liberalization and free trade are the major channels through which globalization can impact on natural stock (Panayotou, 2000). With the ability to increase human carrying capacity by developing new alternatives, eliminating competing species, promoting free trade of locally scarce resources, and new technology, the ecological definition of 'carrying capacity' seems irrelevant to humans (Rees, 1994).

The complexity of interactions between humanity and natural stock can be dated as far back as the origin of man. God made a man, and placed him in the Garden of Eden where he could consume all fruits infinitely, except for one fruit. Because of the limitations in natural stock, Adam ignored the exception, and ate the fruit. The process defined the first critical point in human consumption of natural stock. Eden's adaptation costs beyond the first critical point were clearly defined by God, saying he would work harder to feed his children (or consume more natural stock to develop a growing population).

Arguably, human science exists only to consume the earth in ways that constantly counter the earth's system science. Efforts toward increasing the understanding of the earth's system science in relation to the functionality of biosystems, particularly the human subsystem, are still very limited in various ways. As Costanza (1994) observed that the progress of science has in general uncovered more uncertainty rather than leading to the absolute precision that the lay public often mistakenly associates with "scientific" results. More recently, the idea of sustainability has been used nearly everywhere to define and project's long-term economic benefits resulting from the complex interactions between the human subsystem science and the science system of the earth as a whole.

8.5. Understanding the Concept of Sustainable Development

Sustainability of human consumption can only exist in definite spatial and time scales. This is in contrary with the suggestion by Costanza (1994) that sustainability is a long-term goal. Costanza has given no precise indication of spatial and time scales. Obviously, this long-term goal is based on the notion that sustainability is a form of economic development, which maintains the ecological processes and functions that underpin it and reaps the benefits of improving the quality of life now without denying the future generations a similar opportunity (Brundtland, 1987). Despite conceding the importance of ecological economics in the management of human science systems, the approach to achieving sustainability suggested by Costanza (1994) does not extend far enough to account for the defined limits of natural stock to consumption, nor does it account for the creation of dysfunctional modes (beyond critical limits) of natural stock science resulting from the use of economic instruments (policies) such as "polluter pays".

Arguably, for sustainability to be accepted by environmental scientists, it must have long-term goals and benefits. The most appropriate agents for marketing this doctrine are the environmental economists. Bartlett (1978; 1994; 1997-98) asserted that (a) sustainability has to refer to an unspecified long period of time, (b) steady (population) growth gives very large numbers in modest periods of time. Based on these assertions, Bartlett (1997-98) indicated that the term 'sustainable growth' implies 'increasing endlessly', which means that the growing quantity tends to become infinite in size. The finite size of resources, ecosystems, the environment and the earth leads to the conclusion that sustainable growth, when applied to material things with finite limits, is oxymoronic, Bartlett (1997-98) observed. Further, Daly (1994) stated that sustainable development may be possible if materials are recycled to the maximum degree possible without growth in the annual material throughput of the economy.

Given the analysis presented to this far in this chapter, the application of sustainable development in the exploitation of finite and unstable resource abilities shows a clear lack of understanding the relationship between land stock (human) consumption, limitations, sustainability and development. Pearce and Turner (1989), as well as Costanza and Daly (1992) indicated that maintaining the total natural capital stock at or above the current level is the minimal conditions necessary for sustainability. Based on this assertion, sustainability (S) is proportional to the resource supply potentials (X) and inversely proportional to its limitations. Under natural conditions, stock limitations define the upper limit of production demand (i.e. the stock consumption potentials to meet human demand) and demand rate (Dr). Production demand is a function of the population size consumption (i.e. stock consumption for humanity to survive) (Pc), while demand rate (Dr) is a factor of population development (i.e. developmental consumption per capita) (see Section 8.1 and 8.2). Based on these assertions, sustainability can be expressed as:

Equation 8.1

$$\text{Sustainability} \propto \left(\frac{x}{1}\right)\left(\frac{1}{\text{Natural Resource Limitations}}\right)$$

Where x: natural resource supply ability

The observation demonstrated by equation 8.1 is in line with the general suggestion that natural stock places the basic physical constraints on all human consumption systems (Berkes and Folke, 1991; Pimentel *et al.*, 1996). It also considers the minimal requirements and characteristics of sustainability suggested by Bartlett (1997-98) and Costanza and Daly (1992) (refer to the preceding two paragraphs). Daly *et al.*, (1993) erroneously suggested that natural stock develops. Therefore the economy must eventually stop growing, but can continue to develop (i.e. expand in size). According to Daly *et al.,* the term "sustainable development" therefore makes sense for the economy, but only if it is development without growth (Daly *et al.*, 1993). Irrespective of population numbers, an expansion (i.e. development suggested by Daly *et al.*) of the economy can only be possible if there is an expansion of consumption per capita. This expansion in the case of biofuel production, for example, would demand more of land stock against its finite supply (refer to Sections 8.2 and 8.3). There is an upper limit for natural stock consumption that defines the limit of economic expansion (or development). Consider the demonstration given in Figure 8.3 (Fig. 8.4) where development per capita through biofuel consumption leads to increased demand for production, which is limited by supply of land stock and stock potentials (Fig. 8.7). The highlight made in Figure 8.4 (Fig. 8.3) can be improved further based on the assertion that resource limitations define the performance of total human consumption demand (Dt) and the consumption demand rate (Dr). Using this observation, equation 8.1 can be written as:

Equation 8.2

$$\text{Sustainability} \propto \left(\frac{x}{1}\right) \times \left(\frac{1}{(Dt)\,(Dr)}\right)$$

Where Dt: total human consumption demand
Dr: Consumption demand rate

Following that Dt is a factor of population size and Dr defines the development (De) process, equation 8.2 can be written as:

Equation 8.3

$$\text{Sustainability} \propto \left(\frac{x}{(Ps)\,(De)}\right)$$

Where Ps: population size
De: Development per capita

Natural stock has the ability to resist external pressure systems. According to Berkes and Folke (1991), the structure and function of the ecosystem is sustained by synergistic feedbacks between human societies and their environment. The earth's feedback can be in two forms, namely (a) regenerative, and (b) alternative feedback. Simplified explanations of these processes are: regenerative feedback (m_1) is a condition that occurs when grass, for example, grows new shoots to replace those removed by animals, whereas the condition of land stock that results from excessive animal grazing, soil erosion, defines the alternative mode of natural stock feedback (m_2) (refer to Section 8.4.2). The minimal requirement for sustainability identified by Costanza and Daly (1992) (see earlier discussions of this section) is achieved through regenerative feedback of natural stock effected through optimal human consumption systems. Regenerative feedback (m_1) of natural stock is a constant factor. Including m_1 in the analysis, equation 8.3 can be written as:

Equation 8.4

$$\text{Sustainability} = m_1 \left(\frac{X}{(\text{Ps})\,(\text{De})} \right)$$

Where Ps: population size
De: Development per capita

m_1: a constant (representing the stock's regenerative capacity)

For sustainability to occur, the product of Ps and De must always be 1 and always less than the value of X. This observation shows that:

Equation 8.5

$$\text{Sustainability} = X m_1$$

In the case where growth (human development) is sustainable, the product of Ps and De in equation 5 must always be 1 or less than 1 (i.e. approaching zero) within a land stock consumption cycle. Since human numbers (Ps) continue to grow leading to greater demand for developing a larger population (i.e. increased human consumption pressure on finite (or decreasing) land stock per unit of time), sustainable development becomes a non-practical and non-existent process (i.e. the product of (Ps)(De) becomes bigger than 1).

The analysis given in this chapter to this far answers the question whether the assertion by Brundtland (1987, p. 43) that sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs holds with the development of biofuels. Observations drawn from the analysis confirm the claim by Bartlett (1997) that the high consumption rate per capita in a developed world significantly creates land stock conditions beyond the critical point. This is considered as the world's worst population problem faced by the U.S.A. (Bartlett, 1997; 1997-98; Ehrlich and Ehrlich, 1992). As the number of people increases in space and time, the value of life does not only decline, but also disappears, Isaac Asimov stated (cited in Moyers, 1989; Bartlett, 1997-98). Sustainable development cannot exist in a world characterized by the infinite upper limit of development per capita, whether in a growing, constant or declining human society.

Assuming that optimal stability becomes the concept used to explain an efficient relationship between natural stock supplies and stock consumption by humanity, the relationship with the associated processes given above can be shown as follows:

Equation 8.6:

Optimal consumption stability = $Xm_1/1-(Ps)(Dr)$.

Where: 1 = upper limit for human development consumption per capita (or population size).

For consumption to be optimal, the product of Ps (population size) and Dr must be any figure between 1 and 0 throughout the consumption cycle. Because of the increasing human numbers that consume a fixed amount of natural resources at any given time, as well as the greater demand for developing this growing human population in the same period, the following normally occur:

(a) sustainability of natural resource capital (consumption) is always Zero (0) where the product of Pc and De becomes so high that X becomes zero (0) and for this process to occur, consumption must be at the critical point,

(b) sustainability assumes a negative value where the value of X falls below zero (0); this process occurs where the consumption of natural stock falls beyond the critical point: (a negative value of sustainability defines a condition where there are compulsory changes made in the consumption process of the natural stock here referred to as the conditions beyond the critical point),

(c) once sustainability assumes a negative value, the consumption of that natural resource even when the consumption pressure is removed can never be sustainable (i.e. during this condition, the value of X will always remain negative).

Finally, population growth under natural conditions is naturally regulated and therefore non-destructive to natural stock, while development is characterized by the opposite. Development is purely an intensive resource-consumption process designed to create infinite possibilities through which greater numbers of developed human population can compete and prosper. Development changes human population growth from being a non-destructive process to earth's science systems, creating infinite limits of natural resource demand, greed and dissatisfaction per capita, through which sustainability can never exist. It is immensely surprising for Brundtland (1987), Costanza and Daly (1992), Costanza (1994), Macedo (2000) and others as well to associate sustainability with development. There is no rationality for these researchers to link sustainable human development with sustainable environmental development. The two processes cannot co-exist. For human development to exist infinitely, greater consumption of natural stock must be achieved. However, the supply of natural stock per consumption type is not infinite. That is, natural resources never grow or develop, but are always degraded by human manipulation and consumption of any form for development. As a result, human development cannot be sustainable.

8.6. Tradeoffs for Bio-Ethanol Development

Highlighting briefly the necessary tradeoffs for bio-ethanol fuel development at local and regional scales is the focus of the discussion presented in this section. Detailed analysis of these parameters can be best done in a separate investigation. Nonetheless, tradeoffs necessary for developing bio-ethanol fuel as an industry can be grouped as follows:

1. Agricultural tradeoffs:
    - There is a higher degree of competition between bio-ethanol fuel, electricity, bio-diesel and food for common feedstock sources, land resources, finance and labor. For one process to be successful in a

growing and developing population, the opposite is expected for other processes. Achieving a balance in all food production processes would require a significant reduction in population growth and consumption rates per capita.

- Tradeoffs in feedstock production would have to be made in the following areas: (a) production (input) costs for sugar cane should be based on a rational balance between the eco-efficiency of feedstock production and bio-ethanol fuel economics; (b) growing low cost, but efficient crops (e.g. sweet sorghum) on agricultural land currently under sugar cane for ethanol fuel production; (c) irrigation water for food and bioenergy crops; (d) allocation of soils to feedstock production.
- The diversion of food crops to bio-ethanol fuel production must be on the basis of surplus food production, rather than on increased accessibility to bio-ethanol fuel markets.
- Global and regional trade must not promote lack of food self-sufficiency across the world, but promote regional competitiveness more than dependence (i.e. food surplus should be achieved across the world where physical conditions allow, which can then be used to produce bio-ethanol fuel).

C. Industry tradeoffs:

- A strong partnership between energy producers, suppliers, market developers and bio-ethanol fuel consumers is necessary.
- E10 fuel blend must be considered for short-term fuel developments, while higher blends (e.g. E85, E95 and E100) are being developed as long-term standards fuels.
- Car technologies need to accommodate changes in fuel types, therefore produce cars that increase bio-ethanol fuel market sizes.

D. Economic tradeoffs:

- Economic incentives are necessary for developing the biofuel industry, as demonstrated in the U.S.A. and Brazil, which define the higher costs for adapting to beyond critical conditions in the human consumption adaptation process.

- Regional governments have to subsidize farm input costs to achieve increased job creation, improved farm crop diversification, local energy security, including improvement of the local balance of payment.

E. Policy tradeoffs:

- Policies should be able regulate human energy consumption, more so among the rich.
- Regional policies should promote free trade of bio-ethanol fuel.
- Local and regional policies must define the upper and lower consumption limits for humanity in relation to stock potentials and supply variability.
- Policies should limit population growth per unit of time.
- Policies need to promote the integration of population growth and consumption rates in development planning, even at project levels, rather than to demand more land stock for human failure to regulate the product of sexual activities.
- Policies must allow free market development for biofuels in competitive business environments.
- Policies should not promote inefficiency and lack of creativity in the bioenergy industry through allowing the resource to become an agent for land stock change. That is, tradeoffs would include (a) creating a policy that compromises the market size for gasoline, replacing (or overruling) preceding energy policies, while providing a competitive market niche for bio-ethanol fuel, (b) creating a policy that provides structured incentives and subsidies for bio-ethanol fuel development, promoting bio-ethanol production, and also enhancing consumer confidence the biofuels, without compromising the long-term efficiency of the industry, and (c) policies should balance ethanol fuel growth with land stock limitations (i.e. there must be an upper limit for bio-ethanol development).

Rationalizing the implementation process of the above-indicated tradeoffs at regional and local scales is crucial in achieving greater efficiency of the regional bio-ethanol fuel industry. Tradeoffs associated with policies should benefit the diverse section of developmental and management subsystems, allowing natural stock to retain its natural maintenance capacity.

8.7. Summary and Conclusion

The effectiveness of land stock and feedstock potentials in the production of bio-ethanol (bio-diesel) fuel is dependent on the demand rate of biofuels. Hence, human development per capita, which increases the fuel demand rate, is the principal agent for the creation of critical land stock limits. Population growth alone does not lead to the creation of critical stock, because it is naturally regulated under normal conditions. However, the combination of population growth and development per capita creates the world's worst source of critical stocks. It does so by expanding the upper limit for population growth feedbacks to occur. Therefore, bio-ethanol fuel can lead to critical environments, particularly where energy development per capita can no longer be regulated in the Middle East, but by the local citizens. The assertion that bio-ethanol fuel development enables the creation of a sustainable energy industry on the basis of achieving competitive development per capita, with an infinite upper consumption limit, is baseless and therefore invalid.

Further, specific tradeoffs have to be made to improve the efficiency of the bio-ethanol industry. For a sustainable bio-energy industry to exist, major tradeoffs have to be made by the rich people, who are the major source of the world's environmental problems. Development must not only have the lower limit, but also must have a defined and unyielding upper limit per capita for sustainability to exist, given that natural stock undergoes no growth and certainly no development. It is a fixed entity. The conclusion drawn from the analysis given in this chapter as a whole is that natural stock has a finite upper limit (i.e. it cannot develop or grow), with an infinite lower limit, through which it adapts to irrational human subsystems beyond the critical point.

Next is a summary and conclusion of the observations and assertions made from the opening to the now closing chapter.

Chapter Nine

Summary and Conclusion

Over the last decade, greater technological improvements have been made toward commercializing lignocellulosic ethanol fuel (BBI International, 2002; 2003; Hettenhaus, 1998; U.S.DOE, 2001). However, reducing the production costs of lignocellulosic ethanol fuel still remains the major challenge facing humanity (Aden *et al.*, 2002; Ashworth, undated; McAloon, 2000; U.S.DOE, 2001). In addition to characterizing the variability of lignocellulosic ethanol potentials over southern Africa, the global use of sustainability to qualify the development of biofuels has been examined in this work.

In this dissertation, a viable approach to lignocellulose ethanol production has been investigated in respect to intensive production of cane lignocellulose (bagasse and trash), ethanol economy, fuel market variability, biofuel consumption for human development, as well as land stock limitations. The question whether developing lignocellulose ethanol is a result of increased normal feedstock supplies, or whether is a function of departures of ethanol potentials from these statistical normals, or whether is a result of growing biofuel markets, with increasing scarcity of crude oil in oil deficit countries, or whether is simply a rhetorical reflection of the chimerical viability concept promoted on the basis of the ephemeral principles of sustainable development, or as a product of efficiently combining these parameters with the differential land stock limitations has been investigated. To a much greater detail, the influence of increasing fuel consumption per capita on limited land stock supplies where human population size increases has been established to an important degree at the sub-regional scale. Observations made from this work may be summarized as follows:

A. Lignocellulosic ethanol potentials:

1. A very important relationship exists between ethanol fuel potentials and the spatial distribution of renewable sugar cane lignocellulose over the subcontinent. Sugar mills showing greater potentials for integrating

lignocellulosic ethanol plants currently produce increased amounts of sugar cane bagasse and trash.

2. Annual increase (decrease) in sugar cane bagasse (trash) production increases (decreases) ethanol potentials in all areas of the subcontinent.
3. Generally, trash is very competitive with bagasse in increasing ethanol potentials from cane lignocellulose in all areas of the region. This competitiveness is an attribute of the 30-40mass% (35mass%) average of trash (leaves and cane tops) with a 50% average moisture content (i.e. 15-20bdm%) compared to 14bdm% bagasse composition in 100mass% of the cane biomass above the ground) on one hand. While on the other hand, bagasse has a higher composition of cellulose and hemicellulose than trash per unit mass of cane above the ground.
4. From the 18 sugar mills found in the region, seven (7) have competitive potentials for lignocellulosic ethanol fuel development (i.e. a 40 million gallon (151ML) ethanol plant per annum can be supported with the available cane lignocellulose with less than 50% supplementary feedstock), requiring less supplementary feedstocks, such as sweet sorghum sugar (lignocellulose) and molasses.
5. Years characterized by below normal and extremely low production of sugar cane have greater influence on the development of a competitive lignocellulosic ethanol plant than that developed using statistical normal means, as these conditions account for critical feedstock annual variabilities.

B. Bio-ethanol fuel markets:

1. Blending 10vol% ethanol (i.e. 3.7mass% oxygenate) with 90vol% gasoline (E10) immediately opens the market for bio-ethanol fuel without modifying petrol engines.
2. Fuel blends containing between 10 and 20vol% ethanol fuel in gasoline limit the market size, with higher market development costs for cars dedicated to run on gasoline.
3. In a way similar to found in Brazil, blending 24vol% ethanol with 76vol% gasoline (E24) provides an alternative fuel-blending ratio for term development in the region.

4. E85 fuel blend dedicated to run the flexible fuel vehicles (FFV) improves the market size for ethanol fuel in the long-term leading to increased ethanol fuel sales in the region.

D. Car Technology:

1. All car manufacturers approve the use of gasoline containing 10vol% ethanol (E10).
2. Car warranties are affected by ethanol blends higher than 10vol% in gasoline.
3. Cars dedicated to run on E24 and E85 are already available in global markets therefore requiring no capital investment for new technology development.

E. Local scale population development and biofuels:

The current daily consumption of gasoline per capita is significantly low (0.500-0.700 litres (or 183-256 litres per annum) in Swaziland with a population size of nearly 1 million. Investigating the implications of local bio-ethanol fuel production indicate the following:

1. Population growth and development per capita increases bio-ethanol fuel demand from the current 0.0329l/day using the 10vol% blending ratio with gasoline.
2. Development per capita is the major factor responsible for increased bio-ethanol fuel consumption.
3. Development per capita and population growth lead to a greater demand for bio-ethanol fuel production.

F. Implications of bio-ethanol fuel production on land stock:

1. Population growth and development per capita increases the demand for land stock.
2. Intensive production of bio-ethanol fuel over time leads to the development of land stock conditions defining the critical point (limit) and beyond the critical limit.
3. Developmental consumption of land stock potentials occurs in a cyclical process consisting of a series of stages (limits) where the human adaptation costs increase not only with a new stock consumption cycle, but also with a shift from one land stock stage to another in a single consumption cycle.

G. Viability of lignocellulose ethanol:

1. Viable ethanol fuel production in the region is a function of increased reduction in human population numbers and greater declines in energy consumption rates per capita, a notion that is directly opposite to the concept of sustainable population growth and development.
2. The viability of bio-ethanol fuel production in southern Africa, either from food crops or lignocellulose, is dependent on efficient integration, rationalization and management of all processes contributing to the existence of critical and beyond critical conditions of land stock.
3. Viability of bio-ethanol fuel development is not only a product of efficient technology, low feedstock costs, attractive fuel economics and greater profit margins, but also a credit for balancing the upper limit of human consumption per capita and development with the maintenance capacity of the earth science system. (Maintenance capacity here refers to the capacity of the earth's subsystem science to efficiently regulate the supply of resources for human consumption at any given moment.)
4. Regionally (locally), viability of bio-ethanol fuel development should not mean the fuel potential in satisfying the infinite upper limit of human development, energy consumption per capita, infinitely expanding human population size, and increased human-development competition (or greater profit accumulation) on one hand, while on the other hand leading to the creation of critical and beyond critical supplies of land stock. (Chimerical viability of developmental projects is determined on the bases of balancing numbers in ways similar to sustainability).

H. Sustainability of bio-ethanol fuel production:

1. Sustainable development increases human consumption of non-developing and non-growing land stock per capita, therefore enhancing the creation of critical points and conditions beyond the critical limit of the stock.
2. Bio-ethanol fuel development is not sustainable, but another ephemeral (or chimerical) stage in the human consumption cycle.
3. Sustainable energy development cannot be used to characterize biofuel production, as it neither exists nor can it be achieved.

Until now, potentials for producing lignocellulose bio-ethanol in the southern African sugar industry have not been identified. No the idea of the spatial and temporal variability of these potentials has been suggested for the region. Before now, the purpose of understanding the potential cost for adapting to beyond critical conditions of bio-ethanol fuel production in the region and elsewhere in the world has not been considered in the formulation and planning of developmental projects. It can now be argued to a reasonable degree that natural population growth alone does not lead to critical land stock, nor does it create land stock conditions beyond the critical limit. The opposite however holds for human development where consumption per capita is excessively high. Development positively shifts both the lower limit (poverty line) and the upper limit requirements per capita, where growth of the latter is infinite. In the process, bio-ethanol (more so in the case of bio-diesel) fuel development can create critical land stock potentials, tremendously limiting the environmental benefits of biofuels.

The total viability of bio-ethanol fuel is dependent on various processes, among which, defining the upper energy consumption limit per capita and reducing human numbers that demand greater consumption of non-growing (and non-developing) natural stock deserve urgent consideration. Bio-ethanol fuel development cannot be viable, when assumed on the basis of making more people consume more energy and accumulate more wealth. Yet this rhetorical viability holds the opposite for the consumed natural stock. On the basis of this assertion, chimerical viability manipulates the natural stock in ways that promote oxymoronic principles of sustainable growth and development. A combination of viability and sustainable development in a world defined by exorbitant energy consumption rates per capita and increasing human numbers to be developed is the worst problem that the earth's system science has to face in its history far beyond the observations of Albert Bartlett, Andrew Goudie, Charles Darwin, C.J. Campbell, Colleen Vogel, David Pimentel, Dennis Meadows, Donella Meadows, George Perkins Mash, Jay Hanson, Mary Somerville, Paul Ehrlich, Peter Tyson, Thomas Malthus, Walter Youngquist, and many others. The silent world behaves like a teardrop in the wind, passed through cyclical phases of change where each change defines the unique purpose of human existence: adapting patterns of human avarice.

Findings of the study do not extend far enough to reflect the economics of developing a lignocellulosic ethanol plant at the sub-regional scale, nor highlighting the intra characteristics of bio-ethanol fuel markets in relation to changes in human development. The possible effects of developing the U.S. E85 fuel blend on the economics of bio-ethanol, fuel markets, human development and land stock potentials have not been investigated in this work. Further, efforts to understand the correlation between the various processes examined in this study have not been made. Detailed investigation of these processes at sub-regional scales can contribute to a greater efficiency of the integrated approach for biofuel evaluation and development used in this study. Achieving this process can contribute to minimizing the fuel industry's dependence on government policies, subsidies, incentives and price regulatory structures that significantly limit its competitiveness and long-term total viability.

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Appendix

Appendix 1: Annual sugar cane data

ID	S_MILLS	91/92	92/93	93/94	94/95	95/96	96/97	97/98	98/99	99/00	00/01	01/02.	Tot_Cane_Crush (Ton)
1	Komati	0	0	0	541698	705033	890885	1432315	1501097	1794297	1906776	1907089	10679190
2	Mhlume	1365962	1291604	1245457	1264117	1110675	1237506	1225474	1265309	1288799	1279490	1225997	13800390
3	Simunye	1137775	1168317	1007644	1015563	933338	885951	993582	923729	1074574	1069210	1084457	11294140
4	Ubombo Ranches	1307923	1296825	1265994	1405478	1280876	1454139	1541851	1539027	1965574	1790104	1582545	16430336
5	Pongola	1010468	918687	916758	1162279	983013	1046772	1268902	1231768	1355447	1298228	1355654	12547976
6	Umfolozi	1261365	930261	839170	995856	1177810	1421349	1460560	1171941	1307343	1326005	1172173	13063833
7	Felixton	2249504	1046728	1126148	1519943	1873301	2419709	2444011	1972266	2184041	2557387	2018564	21411602
8	Malelane	1987020	1374873	1383842	889235	881183	1308504	1597206	1616853	1735913	1916766	1761160	16452555
9	Entumeni	214296	162964	247364	332521	293940	379107	408810	459873	365925	399283	405585	3669668
10	Amatikulu	1853923	993037	1076688	1311928	1347582	1880788	1656008	1868018	1651515	1853322	1624590	17117399
11	Darnall	1637369	864781	940797	1116820	1035043	1471602	1370397	1507522	1315623	1566606	1211236	14037796
12	Gledhow	1369212	767411	711459	1144564	1029968	1217064	1227575	1510948	1356731	1522634	1150711	13008277
13	Maidstone	1644953	1012781	894048	1318665	1715235	2141614	2284853	2264130	1668353	2104462	1648747	18697841
14	Noodsberg	1358507	1182293	557341	1099576	949094	1171569	1365276	1776627	1209282	1221144	1565577	13456286
15	Union Coop	561501	614094	370922	657277	621587	663548	946781	831383	881344	889898	744868	7783203
16	Eston	933420	792335	493392	784928	945125	1105513	1079335	1238024	1114382	1397221	1255166	11138841
17	Sezela	1745113	849346	620529	1112885	1740506	2082849	2020876	2118942	1970522	2384737	2187376	18833681
18	Umzimkhulu	1101545	658541	527836	857641	1107197	1331657	1216493	1400235	1249164	1465431	1148041	12063781

Source: South African Sugar Association, Mount Edgecombe, Durban, 2002.

Appendix 2

Mhlume sugar mill annual data					Ubombo Ranches sugar mill annual data				
Year	Aver. cane	Total cane	Mean cane area	Cane Area	Year	Aver. cane	Total cane	Mean cane area	Cane Area
	(Ton/ha)	crushed (Ton)	(Ha)	(Ha)		(Ton/ha)	crushed (Ton)	(Ha)	(Ha)
60/61	120.94	27635	9338	229	64/65	109	443858	10670	4055
61/62	128.80	304847	9338	2367	65/66	105	482488	10670	4582
62/63	120.67	344846	9338	2858	66/67	105	600691	10670	5735
63/64	114.61	296182	9338	2584	67/68	105	613163	10670	5856
64/65	113.58	295238	9338	2599	68/69	106	580478	10670	5494
65/66	101.12	382988	9338	3787	69/70	105	630883	10670	5990
66/67	115.98	416036	9338	3587	70/71	103	670760	10670	6540
67/68	108.91	579735	9338	5323	71/72	100	742313	10670	7389
68/69	98.34	583167	9338	5930	72/73	100	670375	10670	6704
69/70	100.07	645785	9338	6453	73/74	101	716180	10670	7097
70/71	82.77	621481	9338	7509	74/75	101	741436	10670	7331
71/72	97.14	619499	9338	6377	75/76	102	831652	10670	8183
72/73	87.64	676010	9338	7713	76/77	103	773326	10670	7497
73/74	77.31	699371	9338	9046	77/78	102	939138	10670	9168
74/75	100.23	653734	9338	6522	78/79	102	1044049	10670	10212
75/76	107.26	822120	9338	7665	79/80	102	944550	10670	9248
76/77	104.00	862274	9338	8291	80/81	101	1095561	10670	10800
77/78	91.39	888982	9338	9727	81/82	100	1033946	10670	10302
78/79	100.02	857142	9338	8570	82/83	100	1075979	10670	10712
79/80	98.24	939744	9338	9566	83/84	100	1124835	10670	11205
80/81	93.24	978869	9338	10498	84/85	100	1073060	10670	10700
81/82	101.65	1025747	9338	10091	85/86	100	1109517	10670	11050
82/83	87.48	1079715	9338	12342	86/87	100	1404676	10670	13989
83/84	88.46	1077866	9338	12185	87/88	100	1145556	10670	11411
84/85	105.03	939299	9338	8943	88/89	101	1295018	10670	12881
85/86	85.08	1154728	9338	13572	89/90	100	1364212	10670	13629
86/87	104.50	906571	9338	8675	90/91	101	1301675	10670	12931
87/88	96.06	1333324	9338	13880	91/92	101	1307923	10670	12939
88/89	89.22	1146842	9338	12854	92/93	104	1296825	10670	12473
89/90	92.33	1263448	9338	13684	93/94	98	1265994	10670	12873
90/91	98.62	1320646	9338	13391	94/95	103	1405478	10670	13588
91/92	102.24	1365962	9338	13360	95/96	92	1280876	10670	13915
92/93	100.70	1291604	9338	12826	96/97	96	1454139	10670	15171
93/94	96.20	1245457	9338	12947	97/98	100	1541851	10670	15437
94/95	97.37	1264117	9338	12983	98/99	95	1539027	10670	16215
95/96	83.24	1110675	9338	13343	99/00	105	1765674	10670	16795
96/97	95.71	1237506	9338	12930	00/01	101	1790104	10670	17742
97/98	98.80	1225474	9338	12404	.01/02	90	1582545	10670	17630
98/99	97.35	1265309	9338	12998					
99/00	92.19	1288799	9338	13980					
00/01	94.26	1279490	9338	13574					
.01/02	87.34	1225997	9338	14037					

Data supplied by the Swaziland Sugar Association, 2003; Mhlume and Ubombo Ranches Sugar Mills.

Appendix 3: Quarterly petrol consumption data.

Country	Year	Product Vol. (l)	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec	Total (liters)
South Africa	2001	Petrol	2556000000	2520000000	2555000000	2709000000	10340000000
	2000	Petrol	2651000000	2587000000	2541000000	2617000000	10396000000
	1999	Petrol	2685000000	2674000000	2725000000	2777000000	10861000000
	1998	Petrol	2674000000	2679000000	2678000000	2852000000	10883000000
	1997	Petrol	2607000000	2660000000	2720000000	2798000000	10785000000
	1996	Petrol	2617000000	2606000000	2614000000	2729000000	10566000000
	1995	Petrol	2468000000	2512000000	2544000000	2629000000	10153000000
	1994	Petrol	2334000000	2344000000	2455000000	2496000000	9629000000
Swaziland	2001	Petrol	25,129,485	24,298,682	23,715,113	25,354,062	98497342
	2000	Petrol	28,156,128	28,598,169	32,658,862	27,435,798	116848957
	1999	Petrol	26,326,456	27,594,817	29,205,392	31,716,363	114843028
	1998	Petrol	25,520,106	25,622,224	25,375,260	24,948,679	101466269
	1997	Petrol	23,444,419	24,613,118	25,851,707	25,405,811	99315055
	1996	Petrol	*	*	*	*	51534414

Data supplied by South African Department of Minerals and Energy (South African data) and Swaziland Ministry of Natural Resources (Swaziland data).

Appendix 4: Swaziland human population from 1898 to 2001

Census Year	Total Population
1898	43512
1904	85491
1911	108459
1921	112951
1936	156175
1946	187997
1956	240511
1966	395138
1976	518217
1986	708455
1997	980722
* 2001	929488

Source: Swaziland Central Statistics.

Appendix 5: Oil yields and characteristics.

Crop	litres oil/ha	lbs oil/acre	lbs oil/ha
corn (maize)	172	129	323
cashew nut	176	132	330
oats	217	163	408
lupine	232	175	438
kenaf	273	205	513
calendula	305	229	573
cotton	325	244	610
hemp	363	272	680
soybean	446	335	838
coffee	459	345	863
linseed (flax)	478	359	898
hazelnuts	482	362	905
euphorbia	524	393	983
pumpkin seed	534	401	1003
coriander	536	402	1005
mustard seed	572	430	1075
camelina	583	438	1095
sesame	696	522	1305
safflower	779	585	1463
rice	828	622	1555
tung oil tree	940	705	1763
sunflowers	952	714	1785
cocoa (cacao)	1026	771	1928
peanuts	1059	795	1988
opium poppy	1163	873	2183
rapeseed	1190	893	2233

Note: These are conservative estimates -- crop yields can vary widely.

Source: http://www.journeytoforever.org/biodiesel_yield.html

Appendix 6: Oil demand per crop type.

Crop	litres oil/ha	lbs oil/acre	lbs oil/ha	Daily biodieasel - Co.Eff. 100% litres oil	BD Base Demand per capita (l/day)	2x BD Base Demand per capita (l/day)	3x BD Base Demand per capita (l/day)	4x BD Base Demand per capita (l/day)	6x BD Base Demand per capita (l/day)	9x BD Base Demand per capita (l/day)	12x BD Base Demand per capita (l/day)	15x BD Base Demand per capita (l/day)	18x BD Base Demand per capita (l/day)
corn (maize)	172	129	323	16439	0.016439	0.032878	0.049317	0.065756	0.098634	0.147951	0.197268	0.246585	0.295902
cashew nut	176	132	330	16439	0.016439	0.032878	0.049317	0.065756	0.098634	0.147951	0.197268	0.246585	0.295902
oats	217	163	408	16439	0.016439	0.032878	0.049317	0.065756	0.098634	0.147951	0.197268	0.246585	0.295902
lupine	232	175	438	16439	0.016439	0.032878	0.049317	0.065756	0.098634	0.147951	0.197268	0.246585	0.295902
kenaf	273	205	513	16439	0.016439	0.032878	0.049317	0.065756	0.098634	0.147951	0.197268	0.246585	0.295902
calendula	305	229	573	16439	0.016439	0.032878	0.049317	0.065756	0.098634	0.147951	0.197268	0.246585	0.295902
cotton	325	244	610	16439	0.016439	0.032878	0.049317	0.065756	0.098634	0.147951	0.197268	0.246585	0.295902
hemp	363	272	680	16439	0.016439	0.032878	0.049317	0.065756	0.098634	0.147951	0.197268	0.246585	0.295902
soybean	446	335	838	16439	0.016439	0.032878	0.049317	0.065756	0.098634	0.147951	0.197268	0.246585	0.295902
coffee	459	345	863	16439	0.016439	0.032878	0.049317	0.065756	0.098634	0.147951	0.197268	0.246585	0.295902
linseed (flax)	478	359	898	16439	0.016439	0.032878	0.049317	0.065756	0.098634	0.147951	0.197268	0.246585	0.295902
hazelnuts	482	362	905	16439	0.016439	0.032878	0.049317	0.065756	0.098634	0.147951	0.197268	0.246585	0.295902
euphorbia	524	393	983	16439	0.016439	0.032878	0.049317	0.065756	0.098634	0.147951	0.197268	0.246585	0.295902
pumpkin seed	534	401	1003	16439	0.016439	0.032878	0.049317	0.065756	0.098634	0.147951	0.197268	0.246585	0.295902
coriander	536	402	1005	16439	0.016439	0.032878	0.049317	0.065756	0.098634	0.147951	0.197268	0.246585	0.295902
mustard seed	572	430	1075	16439	0.016439	0.032878	0.049317	0.065756	0.098634	0.147951	0.197268	0.246585	0.295902
camelina	583	438	1095	16439	0.016439	0.032878	0.049317	0.065756	0.098634	0.147951	0.197268	0.246585	0.295902
sesame	696	522	1305	16439	0.016439	0.032878	0.049317	0.065756	0.098634	0.147951	0.197268	0.246585	0.295902
safflower	779	585	1463	16439	0.016439	0.032878	0.049317	0.065756	0.098634	0.147951	0.197268	0.246585	0.295902
rice	828	622	1555	16439	0.016439	0.032878	0.049317	0.065756	0.098634	0.147951	0.197268	0.246585	0.295902
tung oil tree	940	705	1763	16439	0.016439	0.032878	0.049317	0.065756	0.098634	0.147951	0.197268	0.246585	0.295902
sunflowers	952	714	1785	16439	0.016439	0.032878	0.049317	0.065756	0.098634	0.147951	0.197268	0.246585	0.295902
cocoa (cacao)	1026	771	1928	16439	0.016439	0.032878	0.049317	0.065756	0.098634	0.147951	0.197268	0.246585	0.295902
peanuts	1059	795	1988	16439	0.016439	0.032878	0.049317	0.065756	0.098634	0.147951	0.197268	0.246585	0.295902

Appendix 7: Land requirement to meet bio-diesel demands.

Land required (ha/day)	Land required (ha/120 days)	2x Land required (ha/120 days)	3x Land required (ha/120 days)	4x Land required (ha/120 days)	6x Land required (ha/120 days)	9x Land required (ha/120 days)	12x Land required (ha/120 days)	15x Land required (ha/120 days)	18x Land required (ha/120 days)
96	11469	22938	34407	45876	68814	103222	137629	172036	206443
93	11208	22417	67250	44834	67250	100876	134501	168126	201751
76	9091	18181	54544	36363	54544	81816	109088	136360	163632
71	8503	17006	51018	34012	51018	76526	102035	127544	153053
60	7226	14452	43356	28904	43356	65033	86711	108389	130067
54	6468	12936	38807	25871	38807	58210	77614	97017	116420
51	6070	12140	36419	24279	36419	54628	72837	91047	109256
45	5434	10869	32606	21738	32606	48909	65213	81516	97819
37	4423	8846	26538	17692	26538	39807	53077	66346	79615
36	4298	8596	25787	17191	25787	38680	51573	64467	77360
34	4127	8254	24762	16508	24762	37143	49523	61904	74285
34	4093	8185	24556	16371	24556	36834	49112	61390	73669
31	3765	7529	22588	15059	22588	33882	45176	56470	67764
31	3694	7388	22165	14777	22165	33247	44330	55412	66495
31	3680	7361	22082	14721	22082	33123	44164	55206	66247
29	3449	6897	20692	13795	20692	31039	41385	51731	62077
28	3384	6767	20302	13535	20302	30453	40604	50755	60906
24	2834	5669	17006	11337	17006	25509	34012	42515	51018
21	2532	5065	15194	10129	15194	22791	30388	37985	45582
20	2382	4765	14295	9530	14295	21442	28590	35737	42884
17	2099	4197	12592	8394	12592	18887	25183	31479	37775
17	2072	4144	12433	8289	12433	18649	24866	31082	37299
16	1923	3845	11536	7691	11536	17304	23072	28840	34608
16	1863	3726	11177	7451	11177	16765	22353	27942	33530

Appendix 8: Bio-ethanol production rates per crop type in relation to daily fuel demands over an 18-year period.

Crop	EtOh yield (l/ha)	Bio-EtOH demand (l/day)	EtOH Base Demand per capita (l/day)	2x EtOH Base demand per capita (l/day)	3x EtOH demand per capita (l/day)	4x EtOH Base demand per capita (l/day)	6x EtOH Base demand per capita (l/day)	9x EtOH Base demand per capita (l/day)	12x EtOH Base demand per capita (l/day)	15x EtOH Base demand per capita (l/day)	18x EtOH Base demand per capita (l/day)
Corn	3000	32877	0.0329	0.0658	0.0986	0.1315	0.1973	0.2959	0.3945	0.4932	0.5918
Sweet sorghum	5200	32877	0.0329	0.0658	0.0986	0.1315	0.1973	0.2959	0.3945	0.4932	0.5918
Sugar cane	5900	32877	0.0329	0.0658	0.0986	0.1315	0.1973	0.2959	0.3945	0.4932	0.5918
Soghum	2320	32877	0.0329	0.0658	0.0986	0.1315	0.1973	0.2959	0.3945	0.4932	0.5918

Appendix 9: Daily land requirements for bio-ethanol production per crop type.

Crop	Land required (ha/day)	Base consumption Land required (ha/120 days)	2x Land required (ha/120 days)	3x Land required (ha/120 days)	4x Land required (ha/120 days)	6x Land required (ha/120 days)	9x Land required (ha/120 days)	12x Land required (ha/120 days)	15x Land required (ha/120 days)	18x Land required (ha/120 days)
Corn	11	1315	2630	3945	5260	7890	11836	15781	19726	23671
Sweet sorghum	6	759	1517	2276	3035	4552	6828	9104	11380	13656
Sugar cane	6	669	1337	2006	2675	4012	6018	8024	10030	12036