# การประเมินความคุ้มค่าทางเศรษฐศาสตร์ สำหรับการปลูกหญ้าเนเปียร์ วิธีประหยัด ภายใต้เงื่อนไขการใช้ทรัพยากรจำกัดมีการบริหารจัดการ และมีผลตอบแทน

**นายทิลล์ แฮเกอเลอร์**



**วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรดุษฎีบัณฑิต**

**สาขาวิชาวิศวกรรมเกษตรและอาหาร**

**มหาวิทยาลัยเทคโนโลยีสุรนารี**

**ปีการศึกษา 2559**

# EVALUATION FOR SUPERIORITY OF ECONOMIC FARMING METHODS OF NAPIER GRASS (*Pennisetum purpureum* SCHUMACH) UNDER THE ASPECT OF RESOURCE SAVINGS, MANAGEMENT AND PROFITABILITY



**Till Haegele**

**A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Agricultural and Food Engineering**

**Suranaree University of Technology**

**Academic Year 2016**

**EVALUATION FOR SUPERIORITY OF ECONOMIC FARMING METHODS OF NAPIER GRASS (*Pennisetum purpureum* SCHUMACH) UNDER THE ASPECT OF RESOURCE SAVINGS, MANAGEMENT AND PROFITABILITY**

Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

Thesis Examining Committee

______________________________

(Asst. Prof. Dr. Payungsak Junyusen)

Chairperson

______________________________

(Asst. Prof. Dr. Weerachai Arjharn)

Member (Thesis Advisor)

______________________________

(Dr. Pansa Liplap)

Member

______________________________

(Prof. Emeritus. Dr. Nantakorn Boonkerd)

Member

______________________________

(Asst. Prof. Dr. Sodchol Wonprasaid)

Member

______________________________

(Asst. Prof. Dr. Wanrat Abdullakasim)

Member

______________________________

(Prof. Dr. Sukit Limpijumnong)

Vice Rector for Academic Affairs and Innovation

______________________________

(Assoc. Prof. Flt. Lt. Dr. Kontorn Chamniprasart)

Dean of Institute of Engineering

ทิลล์ แฮเกอเลอร์ : การประเมินความคุ้มค่าทางเศรษฐศาสตร์ สำหรับการปลูกหญ้าเนเปียร์วิธีประหยัด ภายใต้เงื่อนไขการใช้ทรัพยากรจำกัดมีการบริหารจัดการและมีผลตอบแทน (EVALUATION FOR SUPERIORITY OF ECONOMIC FARMING METHODS OF NAPIER GRASS (*Pennisetum purpureum* SCHUMACH) UNDER THE ASPECT OF RESOURCE SAVINGS, MANAGEMENT AND PROFITABILITY) อาจารย์ที่ปรึกษา : ผู้ช่วยศาสตราจารย์ ดร.วีรชัย อาจหาญ, 139 หน้า.

ในพื้นที่จังหวัดนครราชสีมา ในช่วงหลังการเก็บเกี่ยว เกษตรกรปล่อยพื้นที่การเพาะปลูกให้ว่างเปล่า เนื่องจากการขาดแคลนน้ำ ถ้ามีน้ำเพียงพอต่อการเพาะปลูกตลอดทั้งปีจะมีการใช้ประโยชน์จากที่ดินได้สูงสุด ถึงแม้ว่าปกติการเพาะปลูกจะใช้น้ำฝนตามฤดูกาลเป็นหลัก แต่พืชไร่หลายชนิดขาดคุณสมบัติทนแล้ง โดยเฉพาะในฤดูร้อนของประเทศไทย การเพิ่มขึ้นของการใช้ทรัพยากรธรรมชาติ พลังงานทั่วโลก ทำให้การหาพลังงานทดแทน เช่น พืชผลิตพลังงานได้ และทนต่อสภาพอากาศของไทย จะสามารถเป็นการเติมเต็มพลังงานทางเลือกได้ หญ้าเนเปียร์ (*Pennisetum purpureum* SCHUMACH.) เป็นหนึ่งในพืชพลังงานที่มีคุณสมบัติข้างบนและให้มวลชีวภาพสูงและสามารถปลูกในสภาวะที่น้อยกว่าสภาวะที่เหมาะสม ทั้งนี้การปลูกหญ้าเนเปียร์ยังได้รับการสนับสนุนจากรัฐบาลไทย

เกษตรธรรมชาติ (Natural Farming) ใช้น้ำฝนธรรมชาติ ไม่กำจัดวัชพืช ไม่ใส่ปุ๋ย และไม่ใช้สารเคมีกำจัดศัตรูพืช) ยังไม่เป็นที่รู้จักมากของเกษตรกรในจังหวัดนครราชสีมา เพราะขาดการทดลองศึกษาซึ่งต่างจากระบบเกษตรกรรมแบบดั้งเดิม (Conventiona Farming) เน้นการใช้น้ำ การกำจัดวัชพืช ใช้สารเคมีจำพวกปุ๋ยเคมีและสารเคมีกำจัดศัตรูพืชเพื่อเพิ่มผลการผลิต) เพื่อเป็นอาหารสัตว์จากหญ้าเนเปียร์ ดังนั้นจุดประสงค์ของงานวิจัยนี้เพื่อศึกษาทดลองการปลูกหญ้าเนเปียร์ ด้วยวิธีเกษตรธรรมชาติ โดยการจัดการการปลูกแบบหลากหลายและควบคุมปัจจัยต่าง ๆ เช่น การตัดท่อนพันธุ์ ระยะห่างการปลูก ระยะเวลาการเก็บเกี่ยว นอกจากนี้ยังมีการเปรียบเทียบระหว่างการปลูกตอนต้นและปลายฤดูฝน

ผลการวิจัยพบว่า ภายใต้ เกษตรธรรมชาติ การปลูกแบบดั้งเดิม (โดยใช้ท่อนพันธุ์แบบสองหน่อ, การเก็บเกี่ยวบ่อย ๆ, การปลูกตอนต้นฤดูฝน) ให้ผลชีวมวลน้อยที่สุด ในขณะที่การปลูกแบบทางเลือกใหม่ (โดยใช้ท่อนพันธุ์จากยอด, การเก็บเกี่ยวเพียงครั้งเดียวหลัง, การปลูกตอนต้นฤดูฝน) ให้ผลชีวมวลมากที่สุด ยิ่งไปกว่านั้น วิธีการตัดท่อนพันธุ์ส่งผลต่อผลการผลิตชีวมวลแบบมีนัยสำคัญ (16 Mg DM $ha^{-1}$) การปลูกในปลายฤดูฝน หรือในช่วงฤดูร้อนให้ผลชีวมวลไม่แตกต่างกับการปลูกในฤดูฝน ซึ่งพิสูจน์ศักยภาพการเกษตรในฤดูร้อนได้

การปลูกหญ้าเนเปียร์แบบทางเลือกใหม่ สามารถเป็นทางเลือกในการใช้พื้นที่การเกษตรที่ถูกทิ้งไว้หลังการเก็บเกี่ยวของเกษตรกรได้อย่างมีประสิทธิภาพ

TILL HAEGELE : EVALUATION FOR SUPERIORITY OF ECONOMIC FARMING METHODS OF NAPIER GRASS (*Pennisetum purpureum* SCHUMACH) UNDER THE ASPECT OF RESOURCE SAVINGS, MANAGEMENT AND PROFITABILITY. THESIS ADVISOR : ASST. PROF. WEERACHAI ARJHARN, Ph.D., 139 PP.

BIOMASS/NAPIER GRASS/FARMING SYSTEM/SUSTAINABILITY/WATER

It was recently observed in the Nakhon Ratchasima Province, that farmers let valuable acreage lie fallow due to water scarcity. Indeed, crop water is needed for intense year-round acreage for optimized land use. Although, rain watering is most common, many field crops are not climatically tolerant enough for existing field conditions, particularly during the dry season in Thailand. In the face of ever increasing energy needs from renewable sources, this growing market, from production to energy generation, has promising potential if weather-tolerant energy crops could fill the existing gap. Napier grass (*Pennisetum purpureum* SCHUMACH.) is one such stress-tolerant energy crop, promoted by the Thai government, and able to produce high biomass yield under less-than-ideal field conditions as practiced in the natural farming system.

The natural farming system (*inter alia* rainfed and no additional fertilization) as well as planting Napier grass as an energy crop is not well-known in the Nakhon Ratchasima Province due to the lack of experience compared to the conventional farming system (additional irrigation and fertilization) which is popular for forage production. Hence, identifying a cropping system for biomass from Napier grass

suitable for natural farming was the rationale of this research. Various growing and management factors, including cutting type, intercutting interval, planting density and planting date were investigated in terms of canopy establishment.

From the conventional least-altered system (planting setts, frequent intercutting intervals, initiation at the beginning of the rainy season) produced the least biomass under natural conditions. Setts, two node-containing stem sections, formed sparse populations and frequent intercutting intervals caused almost immeasurably, low yields. A fundamentally altered cropping system (planting terminal cuttings, a full year cropping interval, single-cut instead of intercutting intervals) resulted in significantly higher yields. Furthermore, the cutting type showed significant impact on stand establishment and biomass yield (highlighted by 16 Mg DM $ha^{-1}$). In the dry season, plots produced a statistically insignificant different biomass than in the rainy season initiated equivalents, proving the potential as a dry-season crop.

This fundamentally altered system would be a new approach suitable for filling the gap of unused land by planting Napier grass crops for biomass under natural conditions.

# ACKNOWLEDGEMENTS

I am grateful to those, who by their direct or indirect involvement have helped in the completion of this thesis.

First and foremost, I wish to express my sincere thanks to my thesis advisor, Asst. Prof. Dr. Weerachai Arjharn for his invaluable help and constant encouragement throughout the course of this research. He provided many insightful ideas and comments throughout my Ph.D. studies.

Furthermore, I would like to express my sincere gratitude Dr. Lumprai Srithamma and her family for the continuous support from the first moment on. Without it, I would never have been able to start or complete my work.

I would like to thank Dr. Pansa Liplap, Dr. Nanthagorn, Lida Holowatyj-den Toom, and many others for revision, suggestions and review of my manuscript.

I am grateful to Tarawut Bunnom, Sawitree Khumhom and many other helping hands for their support during the full time of field experiments and beyond.

I am most grateful to my wife, Areenan In-Iam, the most important person, and all her support throughout the period of this research. Finally, I would like to express my gratitude to Stefan Wiegert, my fellow students, Dr. Siriwan Nawong, the staff members of the Centre of Excellence in Biomass and my friends for their support.

Till Haegele

# TABLE OF CONTENTS

**Page**


ABSTRACT (THAI) ..........................................................................................I

ABSTRACT (ENGLISH) ..................................................................................III

ACKNOWLEDGEMENT ....................................................................................V

TABLE OF CONTENTS ...................................................................................VI

LIST OF TABLES ...........................................................................................X

LIST OF FIGURES .........................................................................................XII

**CHAPTER**

**I INTRODUCTION** ..........................................................................................1

1.1 General Introduction ..................................................................................1

1.2 Significance of the Problem .......................................................................2

1.3 Basic Assumptions ....................................................................................3

1.3.1 Cropping Systems ..............................................................................3

1.3.2 Utilization of Napier Grass ..................................................................4

1.3.3 Purpose of the Study ..........................................................................5

1.4 Objective and Research Hypothesis ..........................................................5

1.5 Scope and Limitation of the Study .............................................................6

**II BACKGROUND THEORY AND LITERATURE REVIEW** ...............................8

2.1 Energy Statistics .........................................................................................8

2.2 Utilization of Biomass .................................................................................9

# TABLE OF CONTENTS (Continued)


**Page**

2.3 Residues and Biomass as Byproducts for Energy Generation ....................12

2.4 Biomass Characteristics of Napier Grass for Conversion into Energy ........14

2.5 Sustainability and Cropping Systems........................................................17

2.5.1 Environment and Agro-ecosystems................................................17

2.5.2 Agricultural Systems .......................................................................18

2.5.2.1 Conventional Farming Systems ......................................18

2.5.2.2 Alternative Farming Systems ..........................................19

2.5.2.3 Future Expectations from Agricultural Systems ...............21

2.6 Thailand's Water Situation ..........................................................................22

2.7 The Alternative Energy Development Plan ...............................................23

2.8 The Gross Domestic Product and Thailand's Infrastructure........................24

2.9 Biomass Production from Napier Grass......................................................25

2.9.1 Introduction .........................................................................................25

2.9.2 Yield Productivity ................................................................................25

2.9.3 Turning Napier Grass into a Field Crop (from Plant to Crop) ..........27

2.9.4 Propagules and Field Propagation ....................................................29

2.9.5 Vegetative Reproduction ..................................................................31

2.9.6 Ecology...............................................................................................33

2.9.7 Physiology and Stress Physiology....................................................34

2.9.8 Naturalization .....................................................................................34

**III MATERIAL AND METHODS**......................................................................36

# TABLE OF CONTENTS (Continued)

**Page**

3.1 Experimental site ....................................................................................36

3.2 Experimental Design and Set-up .............................................................37

3.3 Cultivation Method ...................................................................................42

3.4 Determination of Plant Material ...............................................................44

3.5 Agronomic Parameter Analysis .................................................................46

3.6 Plant Sampling and Data Analysis ............................................................47

3.7 Statistical Analysis ....................................................................................48

**IV RESULTS AND DISCUSSIONS** .............................................................49

4.1 Plant Material ............................................................................................49

4.2 Competitive Weeds and Pests ...................................................................49

4.3 Weather at the Study Site ..........................................................................53

4.4 First Experiment (07/05/2012 until 27/04/2013).......................................57

4.4.1 Summary of First Experiment ..........................................................73

4.5 Second Experiment (07/05/2013 until 22/04/2014) ...................................73

4.5.1 Summary of Second Experiment.......................................................86

4.6 Third Experiment (07/05/2013 until 22/04/2014) ......................................86

4.6.1 Summary of Third Experiment..........................................................92

4.7 Comprehensive Experiment (2012 until 2014) ..........................................92

4.7.1 Summary of the Experiment............................................................104

4.8 Summary of Treatments and Farming Systems .......................................106

4.8.1 Biomass Yield .................................................................................106

# TABLE OF CONTENTS (Continued)

**Page**


4.8.2 Cutting Type.......................................................................................107

4.8.2.1 Terminal Cuttings..........................................................107

4.8.2.2 Planting Method and Density of Setts.............................107

4.8.2.3 Long Stem Sections........................................................109

4.8.3 Cutting Regime..................................................................................110

4.8.4 Planting Date......................................................................................111

**V CONCLUSIONS**......................................................................................114

5.1 Conclusions.............................................................................................114

5.2 Recommendations for Future Work.........................................................115

REFERENCES...................................................................................................117

BIOGRAPHY.....................................................................................................139

# LIST OF TABLES

**Table** **Page**

2.1 Variation of concentrations of cellulose, hemicellulose and lignin of Napier grass parts....15

3.1 Physical and chemical soil characteristics of the experimental field site ....36

3.2 Experimental set-up, treatments and attributes of the Napier grass cultivar from SUT campus for testing altering farming systems under natural conditions from 2012-2014....39

3.3 Experimental set-up, treatments and attributes of the Napier grass cv. ˈPakchongˈ from SUT campus for testing altering farming systems under natural conditions from 2013-2014....42

3.4 Measurements of tested cutting types before planted in field in the experiment 2012....43

3.5 Measurements of tested cutting types before planted in field in the experiment 2013....43

4.1 Competitive weeds on Napier grass fields....51

4.2 Pest and disease causing disorders monitored during the experiment....54

4.3 Effect of cutting type on dry mass on a four-monthly intercutting interval in the experimental period 2012 to 2013 ....60

4.4 Effect of stem section length and planting method on DM at two different harvesting dates in the experimental period 2012 to 2013....62

# LIST OF TABLES (Continued)

**Table** **Page**

4.5 Effect of intercuts and cutting type on dry mass in the experimental period 2012 to 2013 .......... 63

4.6 Effect of initiation density and planting method of setts on DM yield in the experimental period 2012 to 2013 .......... 65

4.7 Effect of regular and late planting date of setts on dry mass in the experimental period 2012 to 2013 .......... 67

4.8 Evaluation of agronomically important growth parameters of Napier grass under natural conditions in the experimental period 2012 to 2013 .......... 68

4.9 Effect of cutting type and planting method on DM at two different harvesting dates in the experimental period 2013 to 2014 .......... 79

4.10 Effect of intercuts and cutting type on dry mass in the experimental period 2013 to 2014 .......... 79

4.11 Effect of initiation density and planting method of setts on DM yield in the experimental period 2013 to 2014 .......... 81

4.12 Effect of regular and late planting date of setts on dry mass in the experimental period 2013 to 2014 .......... 83

4.13 Evaluation of agronomically important growth parameters of Napier grass under natural conditions in the experimental period 2013 to 2014 .......... 84

4.14 Effect of planting method and cutting type on dry biomass of Napier grass cv. 'Pakchong' at two harvesting dates in the experimental period 2013 to 2014 .......... 89

# LIST OF TABLES (Continued)

**Table** **Page**

4.15 Effect of planting method and cutting type on dry biomass of Napier grass at two intercutting intervals during the years 2013 to 2014 ....................96

4.16 Effect of cutting type and sett planting method on dry mass of Napier grass in the experimental periods during the years 2012 to 2014.....................97

4.17 Effect of one-cutting type and combined cutting types on dry mass of Napier grass in the experimental periods during the years 2012 to 2014.........98

4.18 Effect of cutting type, initiation density and harvesting season on DM yield of two different Napier grass cultivars.................................................100

4.19 Effect of initiation density and planting method of setts on DM yield of two different Napier grass cultivars..........................................................102

4.20 Effect of late planting date of setts on DM yield ..........................................104

4.21 Results of ANOVA to test for effects of experimental year on agronomically important development parameters at the end of the rainy season planting of Napier grass in 2012 and 2013 .................................................................104

# LIST OF FIGURES

**Figure** **Page**

2.1 Scheme of biomass byproducts, occurrence and utilization handling ..............13

2.2 DM yield of Napier grass considering production method and location ..........27

2.3 Napier grass parts for asexual propagation ......................................................30

2.4 Regeneration stages of roots and shoots of two different cutting types of Napier grass ..........................................................................................32

3.1 Planting patterns of entries consisting of different cutting types for the experiments from 2012-2014..........................................................................40

3.2 Classification scheme for evaluation of photosynthetic active leaf area ..........46

4.1 Monthly precipitation and average temperature for the duration of the field experiments at SUT; data obtained from the field site ............................55

4.2 Produced biomass from cutting types in response to quantities of consumed rainfall; yields and precipitation accumulated for intercutting intervals ..........58

4.3 Distribution of dry mass yields and specific standard deviation of entries of Napier grass after completion of the study from 2012 to 2013 ....................58

4.4 Yield response on intercutting interval and season...........................................61

4.5 Relative distributions for fresh mass (FM) input and output sorted by cutting type and planting method in the experimental period 2012 to 2013.................66

4.6 Tiller recruitment of cutting types or planting method in the experimental period 2012 to 2013 ..........................................................................................70

# LIST OF FIGURES (Continued)

**Figure** **Page**

4.7 Produced biomass from cutting types in response to quantities of rainfall during second experiment ........ 74
4.8 Distribution of dry mass yields and specific standard deviation of entries of Napier grass after completion of the study from 2013 to 2014 ........ 76
4.9 Relative distributions for fresh mass (FM) input and output sorted by cutting type and planting method in the experimental period 2013 to 2014........ 82
4.10 Distribution of dry mass yields and specific standard deviation of entries of Napier grass cv. 'Pakchong' after completion of the study from 2013 to 2014 ........ 88
4.11 Relative distributions of entry-specific produced biomass sampled at two intercut intervals in the experimental period 2013 to 2014 ........ 90
4.12 Relative distributions for planting invested biomass input and yield output sorted by planting method and cutting type of Napier grass cv. 'Pakchong' in the experimental period 2013 to 2014 ........ 91
4.13 Experiment specific produced biomass from entries in response to quantities of rainfall during experiments from 2012 to 2014........ 94
4.14 Relative distribution and effect of season on biomass production ........ 103

# CHAPTER I

# INTRODUCTION

## 1.1 General Introduction

Agricultural products have supplied human society since the beginning of settled agriculture thousands of years ago. The production of commodities in mono-cropping systems has become a milestone in pre-industrial production and the key to success in crop management and has ensured sufficient food supply. Mono-culture systems are characterized by a high density of individual plantlets of a certain crop through which yields increase and acreage use is intensified, resulting in maximum productivity. The modern agro-industry still cultivates crops in mono-culture systems since it is still the most efficient method.

The productivity of agricultural production in the $20^{th}$ century was successively improved by supplementing agro-resources with chemical fertilizer and irrigation (Lichtfouse et al., 2009). Consequently, resource supplementation also enabled the reclamation of new acreage in low-fertile agro-ecosystems. On the other hand, biased resource management has led to exploitation, erosion and land degradation resulting in desertification within a few decades (Lal, 2001). After it became clear that exploited agro-resources cannot be replaced arbitrarily by external inputs, a fact also confirmed by economics, contemporary agriculture focusses on the long-term use of existing agro-ecosystems through the conscious management of natural resources.

Nevertheless, fresh-water scarcity forces farmers to let fertile farmland lie fallow (Beeman and Pritchard, 2001).

In addition, agricultural scientists, farmers and the public have to face new challenges: Climate change, life-cycle assessment, energy footprint, sustainability, conflicts of land use, food supply for a growing world population, and most currently, supplying the increasing energy needs by renewable sources. The requirements of agro-products for multiple industrial processes have promoted non-food crops but have also evoked land-use conflicts. The public as well as scientists are discussing whether the available agro-resources should be used mainly for food or industrial use (De Groot, 2006; Lewandowski and Schmidt, 2006).

Hence, research on low-demanding industrial crops for cropping under conditions in which food crops cannot be cultivated or as side crops, could present a solution for land-use conflict.

## 1.2 Significance of the Problem

Rainfed agriculture is most common in Thailand since additional water for crop irrigation has already become scarce with few options for a year-round supply (i.e. by reservoirs). The largest acreage comprises Thailand’s central and northeastern regions, which are strongly characterized by monsoon-influenced seasonal farming periods (dry and rainy season). In the central and northeastern regions, rice is the main crop and can be grown only during the rainy season, leaving a time gap for the cultivation of side crops in the climatically unfavorable dry period. All crops during the dry period require high inputs of external resources which strongly conflict with economic aims. For instance, additional fertilization is most effective in combination with irrigation but farmers must bear the costs for both. Furthermore, as a fact that has been criticized for years, highly productive farmland lies completely unused in Thailand because farmers can hardly afford crop inputs for the head crop (i.e. chemical fertilizer) (Vangnai, 1981). Taken together, a single main crop during the rainy season provides a low income and keeps development of rural areas static as long as production costs do not decrease or until existing acreage is used more efficiently by year-round farming. Particularly in the Nakhon Ratchasima Province, it can be observed that regional farmers prefer to leave fields completely unused or compromise by growing crops such as cassava or sugarcane for unusually long periods (one-to-two years until harvest instead of frequent intercutting intervals). Both crops lose quality with expanding intercutting periods and have negative effects on the environment (i.e. chemical weed control, land clearance by slash and burn).

## 1.3 Basic Assumptions

It is assumed that farmers would be successful in reversing the reasons for leaving farmland fallow completely or, during a certain season, by the reduction of production costs for specific crops (i.e. environmentaly tolerant crops) or by a more efficient farming system. Such an alternative crop for external-input-free production by an alternative farming system would avoid fallow farmland by furnishing an additional income and helping to develop rural areas in Thailand. Profits could be maximized by raising an environmentally tolerant crop.

### 1.3.1 Cropping Systems

The conventional system of raising Napier grass for the production of fodder in Thailand is well known, even though that system requires high external inputs. Napier grass (*Pennisetum purpureum* SCHUMACH.), however, is known for being a low-demanding crop which still produces promising yields under reduced fertilization or irrigation (Knoll et al., 2011). Therefore, the system of natural farming, as its main concept, is letting plants grow just as they do in natural fertile forest soil. As a low-demanding drought-tolerant crop, Napier grass for biomass has a potential to become an interesting alternative to fodder production, compatible with natural farming and promotes sustainable management. Napier grass matures more quickly under natural farming and becomes un-digestible for cattle but more appropriate for biomass (Johnson, Guerrero and Pezo, 1973). Secondly, too little is known about yield potential, management or crop development for Napier grass during the dry season and needs to be investigated. Finally, new markets - from production to generation - must be established in Thailand.

**1.3.2 Utilization of Napier Grass**

Thailand's economy and society will consume more energy in the upcoming years. The Thai government aims to satisfy the expected demands mostly by national resources. Such resources could be byproducts from agriculture such as organic waste, residues or biomass from energy crops (Ministry of Energy and Electricity Generating Authority of Thailand, 2016). Agro-products are renewable and carbon-dioxide neutral, and thus, help to reduce greenhouse gas emissions. Thailand's infrastructure (huge acreage, smallholders and small-scale power plants) and new conversion technologies have a potential to satisfy the expected energy needs from renewable resources and could be locally and regionally profitable.

Recently, Thailand's government promoted Napier grass in the Alternative Development Plan as a new year-round biomass supplier for conversion into bioenergy (National Energy Policy Council, 2014). Its establishment in arid areas is displayed by the diazotrophic and thermophilic life, drought tolerance and a C4-photosynthesis. Napier grass's interesting eco-physology has a potential as a crop for dry season farming. Interestingly, the yield of naturalized Napier grass without farm care showed a potential for economic use and insignificant effects on the environment. Hence, Napier grass should be suitable for cultivation under less-than-ideal conditions as found in the natural farming system without risking quality characteristics (physical and chemical) which are an important property for conversion into energy.

### 1.3.3 Purpose of the Study

Identifying a high-yielding and profitable farming system under natural conditions for Napier grass for bioenergy instead of fodder could help to avoid leaving farmland unused in the future without land use conflict. Residues for bioenergy conversion from rice, which is only available in season, could be combined with Napier grass's biomass for a year-round supply or replace it completely.

## 1.4 Objective and Research Hypothesis

Increasing needs for biomass for bioenergy turned Napier grass into a new energy crop in Thailand. The natural farming system is more attractive compared to others due to their uneconomical features. In Thailand, Napier grass is commonly cultivated in the conventional farming system but little is known about yield performance from alternate farming systems. General and specific information on fundamental adaptions of farming practices and systems from conventional to natural conditions are lacking. A farming system and practice comprises cutting type, planting density, harvesting intervals and best planting time. Hence, the objective of this study is to investigate the effect of alternate farming practices, including cutting types, initiation cane density, ratooning frequency and inception time, on yield and stand development of Napier grass under natural conditions.

Naturalized Napier grass keeps its positive characteristics (chemical and physical) under less than ideal conditions (i.e. heat, drought). It is hypothesized that an altered farming system with reduced inputs will produce profitable outputs which would help to promote farming during the dry season and improve the intensity of farmland use. Furthermore, biomass for conversion from Napier grass crops from a sustainable improved farming system would keep farmland fertile and have fewer negative effects on the environment.

## 1.5 Scope and Limitation of the Study

This study entails an investigation to determine a Napier grass biomass production system with reduced inputs for cropping on regional unused farmland. This thesis consists of three in-situ field experiments on the campus of the Suranaree University of Technology (SUT)/Nakhon Ratchasima province from 2012 to 2014. An undetermined cultivar from the SUT campus and the 'Pakchong' cultivar were investigated on a field site. Soil type and environment were perceived typical for the Nakhon Ratchasima province. Slightly or fundamentally altered treatments from those commonly practiced in Thailand, were tested for effects and farming potential as well as under natural field conditions. Each experiment consisted of four treatments (1: cutting density, 2: cutting type, 3: ratooning frequency and 4: inception time). Firstly, the four experimental treatments with the unknown hybrid from the SUT campus were tested and, secondly, for effect verification experiments were replicated in the next year. Simultaneously the cv. ‘Pakchong’ was tested in a third parallel experiment. Each experiment started in May and finished after one year.

All experimental treatments were tested in a completely randomized block design and biomass yields were analyzed for statistically significant effects (ANOVA and *t*-test).

,

# CHAPTER II

# BACKGROUND THEORY AND LITERATURE REVIEW

## 2.1 Energy Statistics

Thailand's economy, and thus the gross domestic product, is prognosticated to continue its rapid development in the upcoming years. Such rapid social developments need infrastructures and are accompanied by growing energy demands for the future (Panklib, Thaicham and Khummongkol, 2016). Therefore, the Thai government has developed a Power Development Plan (PDP). The PDP has estimated that energy demands will double from 2009 to 2021 and will continue to grow (Ministry of Energy and Electricity Generating Authority of Thailand, 2016). The domestic primary energy supply accounted for 134,308 ktoe compared to a final energy consumption of 75,214 ktoe in 2013. Industry (36.2%), transportation (35.8%) and residential (15.1%) sectors consumed the most energy while the agriculture sector consumed the least with 5.2%. By producing many residues, that are a suitable resource for alternative energy generation, the agricultural sector is an important economy in Thailand. Nevertheless, 76.22% of the final energy consumption was generated from fossil fuels as opposed to 10.94% from alternative energy sources (Department of Alternative Energy Development and Efficiency, 2016). However, biomass for energy is a growing market especially because of the government's support and the Alternative Energy Development Plan (AEDP) which aims to reduce fossil-fuel consumption to 25%.

Thus, the energy gap shall be filled through the promotion of alternative and renewable sources by 2021.

## 2.2 Utilization of Biomass

Thailand has committed to the United Nations Framework Convention on Climate Change for the Kyoto Protocol to reduce greenhouse-gas emissions (carbon dioxide, $CO_2$) and, consequently, global warming and climate change (Thanarak, 2012). The carbon cycle of biomass is neutral due to the fact that $CO_2$ emissions are not larger than the quantity fixed by photosynthesis. Hence, biofuels from biomass are not included in the $CO_2$ balance of the Kyoto protocol (Stöcker, 2008). Agriculture and transportation (second largest $CO_2$ emitter in Thailand) are two important economic sectors in Thailand. Agriculture produces abundant biomass which can be converted into biofuels for transportation. Nevertheless, as long as biomass is $CO_2$ neutral, infrastructures for biomass transportation from field to power plant - and power plant technology itself - can influence the balance from neutral to consuming and hope for financial profitability (Barz and Delivand, 2011). Furthermore, the physical structure of biomass influence synthesis gas (syngas) composition as biomass is composed of miscellaneous and varying amounts of elements (Demirbaş, 2001b). Thailand's agricultural regions can roughly be divided into south, central, north and northeastern regions. In the south, oil palms are preferred as the permanent crop while in the remaining areas, herbaceous crops with short cropping periods such as rice, maize and sugarcane are grown mostly on plantations (Garivait et al. 2006; Thanarak, 2012). The various crops yield diverse waste and residues that require specifically adapted power-plant technology for each feedstock (Arjharn et al., 2012).

Power-plant technology is quite common in Thailand as gasification technology is fully commercial. 156 biogas power plants (265.23 MW total capacity) and 994 biomass power plants (2,320.78 MW total capacities) were counted for statistics in 2013. Biomass power plants obviously form the majority due to the important agro-industry, producing approximately 68% of the total energy from renewable sources (Department of Alternative Energy Development and Efficiency, 2016; Johansson et al., 2012). Smallholders are the largest producer group of agro-products. Particularly the central and northeastern regions form the largest acreage in structured rural communities. Investigations found that the biomass supply within a 10-km radius around a power plant is economically advantageous, favoring small-scale biomass power plants (100 KW output power) for rural communities. Those power plants can be used as co-energy deliverers with less environmental pollutant emissions than direct biomass combustion in cook stoves (Arjharn et al. 2008; Barz and Delivand, 2011; Chanthunyagarn, Garivait and Gheewala, 2004). A pilot-scale power plant successfully converted all community-produced biomass-from wood to other residues irrespective of origin - effectively into syngas (Arjharn et al., 2012).

Using the thermochemical processes of the gasification technology, small-scale power plants convert biomass into so-called syngas, which contains carbon monoxide (CO), hydrogen ($H_2$) and methane ($CH_4$) and is combustible in engines and generators. The downdraft-fixed bed gasifier is commonly used for small scales because of its efficiency. The process of gasification starts with drying the biomass and is followed by pyrolysis, combustion and reduction processes. The thermochemical-conversion method strongly depends on the temperature during the pyrolysis process, affecting the net yield of liquid products, char and syngas, and is thus separated to low (700–

1000°C) and high temperature (1200–1600°C) gasification (Demirbaş, 2001a). In the downdraft gasifier after pyrolysis, all gaseous, liquid and solid products are combusted under an oxygen supply. The temperature increases as a result (1000°C) and the residual heat can be used for drying again. In the combustion process, solid products such as tar are converted into hydrogen. Simultaneously, carbon-containing products (char and ash) are converted into hydrogen and carbon monoxide (Arjharn et al., 2012; Stöcker, 2008). Gasification efficiency ranges regularly between 70 and 80%. If generator efficiency is low, through suboptimal technical support, the overall system efficiency can drop drastically (Assanee and Boonwan, 2011; Barz and Delivand, 2011).

In contrast to first-generation bioethanol which was converted from carbohydrate-rich plants, evoking controversial public ethics discussions on converting food plants into energy (sugar from sugarcane or starch from maize), second-generation biofuels developed biomethanol synthesis or Fischer-Tropsch (FT) biomass-to-liquid (BTL) from broadly available syngas. Syngas, available by the pyrolysis of wood-based biomass (lignocellulose rich), is used as a chemically valuable processing product to BTL instead of combustion. Lignocellulose comprises cellulose, hemicellulose and lignin, whereas the first two are separated from lignin and subsequently converted into bioethanol (Stöcker, 2008). Second-generation biofuel conversion is more efficient than first-generation, or in other words, more carbon dioxide can be reduced. Gasification and pyrolysis of biomass with a catalytic upgrading of the products (syngas) will be the future of biomass conversion processes (Dahiya, 2014; Stöcker, 2008). As a result, lignin is the most chemically valuable raw material for BTL and needs are arising for lignin-rich energy plants and, thus, available acreage for cultivation.

## 2.3 Residues and Biomass as Byproducts for Energy Generation

Thailand has a large and important agro-industry on 114.6 million rai (18.34 million ha). Healthy crops produce huge amounts of fresh herbage, needed for the ripeness of crops, which can be used as valuable green manure on the fields or as biomass feedstock for the bioenergy industry. The residues and multiple organic wastes as byproducts from the head crops were recognized as an increasingly important renewable-energy source in recent years.

Thailand's agro-industry is the world's largest rice producer and rice plants are cropped on 55% of the existing acreage. Thus, biomass for the bioenergy industry is steadily produced during the season of rice farming (Reda, Tripathi, and Mozumder, 2013). Rice crops are grown for grains and much straw-biomass remains as green manure on fields. Rice herbage accumulates progressively after initiation (input) and the process is stopped with the harvest of rice grains (output). The total produced biomass can be roughly classified into non-plantation (process based) and plantation (field based) biomass, depending on its occurrence, shown in Figure 2.1 (Barz and Delivand, 2011; Papong et al., 2004). In contrast to fresh biomass that remains on the field, husk is produced during the subordinated milling process and is used as biomass fuel (approximately 5.67 Mio mt/yr husk). Besides rice, three other head crops were estimated to produce large quantities of biomass and residues in 2010, namely sugarcane (17.51-20.42 Mio mt/yr bagasse), oil palm (1.37 Mio mt/yr empty bunches) and maize (1.31 Mio mt/yr corn cob) (Sajjakulnukit et al., 2005). Recent estimations of total accumulated residues from agro-industry vary between 61 to 80 Mio mt/yr$^{-1}$ which equals almost 430 PJ of energy (Papong et al., 2004; Prasertsan and Sajjakulnukit, 2006). However, it is estimated that only 20 Mio mt are utilized for power generation and most of the produced biomass, 41 Mio mt or 66%, remains completely or partly unused on the plantations (Prasertsan and Sajjakulnukit, 2006). Harvesting methods, intercutting intervals, soil fertility and rural use determine the utilization of biomass byproducts. However, to intensify the utilization of biomass from residues - also the large biomass quantities from field-based production - ought to be included in energy generation.

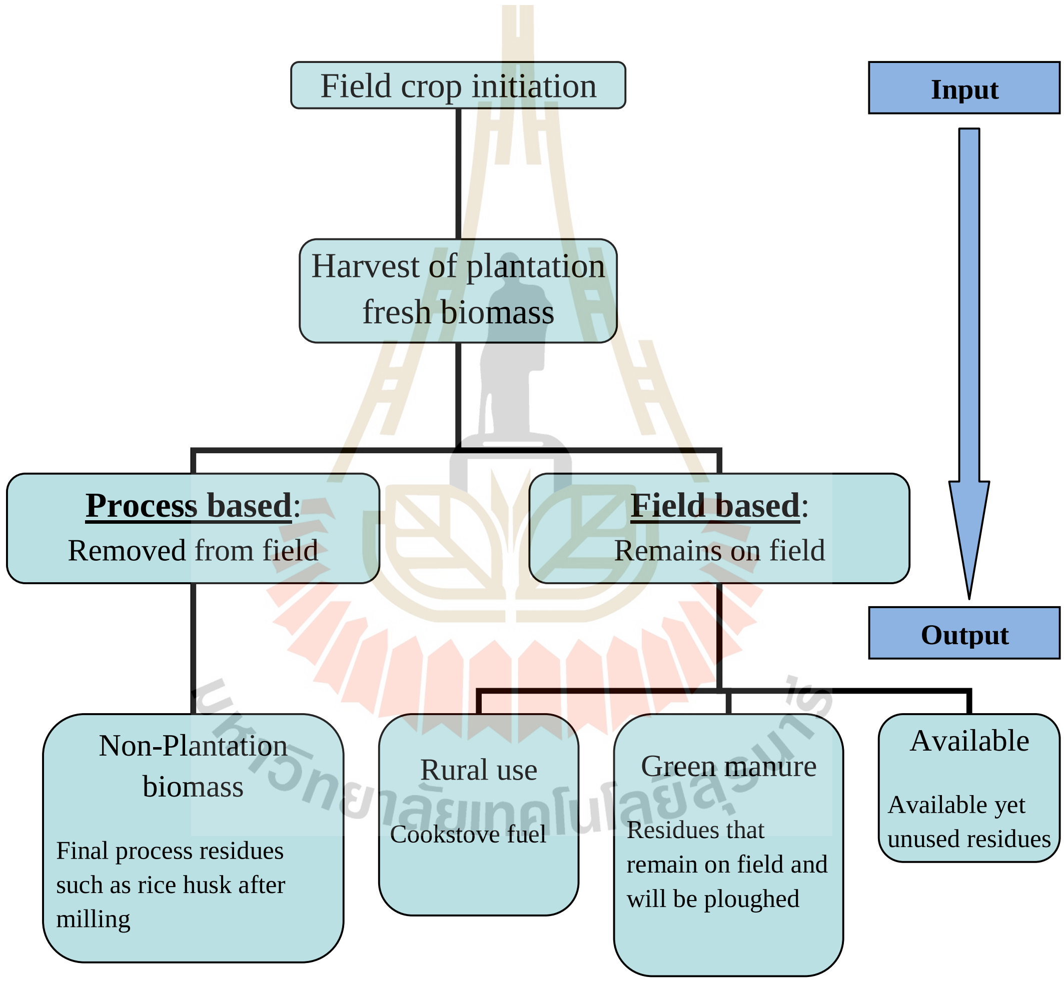



**Figure 2.1** Scheme of biomass byproducts, occurrence and utilization handling.

Estimations of produced residues have been constant for many years, meaning secure supplies from a constant field area. Thailand’s bioenergy industry needs secure and steady biomass suppliers. The current subordinated utilization of biomass originates from a small amount of process-based residues. As a result, increasing amounts of biomass or residues are needed for meeting the aims of the AEDP a goal that can be realized by increasing agricultural production or including unused plantation biomass. Admittedly, Thailand's agro-industry is based on smallholders and established infrastructures (head crops, markets for selling and channels of distribution) that limit acreage expansion. Facing the need for increased year-round biomass quantities to meet the aims of the AEDP, Thailand's government started to promote energy crops instead of residues by guaranteeing fixed purchasing to motivate farmers toward crop change (National Energy Policy Council, 2014).

## 2.4 Biomass Characteristics of Napier Grass for Conversion into Energy

The availability of arable farmland is a constant problem as existing acreage is needed primarily for food and fodder production. Also, energy should not be won from ethically problematic sources (Pimentel and Hall, 1984). In the case of Napier grass, which is commonly cropped for fodder in Thailand, soft fresh biomass is preferred by cattle. Cattle prefer the soft herbage which is nonpoisonous and easy to digest and are reluctant to eat fiber-rich fodder as found in the matured stems of Napier grass, which are excreted undigested during rearing (Chen, Wang, and Hsu, 2006; Rahman et al., 2006). Interestingly, such physical structures as fibers and other cell-wall constituents rich in lignocellulose are of high interest for BTL. Napier grass, as a tall grass, forms fiber-rich stems which, with successive maturity, are cut away mechanically by short intercutting intervals, suppressing stem elongation for forage production. Previous studies described that the chemical composition of Napier grass varies within plant parts (Schank et al., 1993). The highest concentration of crude protein (CP) can be found in leaves while cellulose, hemicellulose and lignin are structures of the cell-walls. Hemicellulose, as the structure for the primary cell-wall, occurs in highest concentrations during cell division whereas cellulose and lignin strengthen plant cells during the maturing process (Throm, 2007). Investigations found that concentrations of CP and cellulose decreased while hemicellulose and lignin (80%) increased with longer growing periods (Ansah, Osafo and Hansen, 2010; Johnson, Guerrero and Pezo, 1973). The variation of the lignocellulosic composition of Napier grass, separated into leaves and stems, is shown Table 2.1.

**Table 2.1** Variation of concentrations of cellulose, hemicellulose and lignin of Napier grass parts.

| | % DM | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Cellulose | | | Hemicellulose | | | Lignin | | |
| | Leaf | Stem | Total | Leaf | Stem | Total | Leaf | Stem | Total |
| [1] | 37.39 | 45.29 | 42.39 | 26.51 | 20.58 | 22.75 | 6.66 | 8.48 | 7.31 |
| [2] | 36.28 | 40.69 | 42.76 | 24.00 | 22.63 | 23.17 | 10.58 | 12.85 | 11.64 |
| [3] | 36.04 | 41.24 | | 30.55 | 24.85 | | 3.66 | 8.86 | |

[1] (Rengsirikul et al., 2013), [2] (Ansah et al., others, 2010), [3] (Vermerris, 2008)

Lignocellulose, specifically lignin, is an eligible feedstock for thermochemical bioenergy synthesis and is found in stalks. Hence, stalks-which form during longer harvest intervals-as cropping product became more important than the well digestible fresh herbage (Chen, Wang and Hsu, 2006). Moreover, the physical properties and chemical composition of Napier grass fibers changed and the composition of cellulose and lignin increased as hemicellulose decreased when treated in an alkali solution, extending utilizing feasibilities (Reddy et al., 2009). Taken together, frequent intercutting intervals produce much biomass with reduced chemical-composition quality for bioenergy in contrast to matured stands.

The AEDP-calculated syngas and Compressed Bio Gas (CBG) generation from Napier grass had a heating value of 14-18 MJ/kg in accordance with an average energy content of 16.36 MJ/kg for the whole plant (Rengsirikul et al., 2013). A recent investigation found a higher heating value of 18.11 MJ/kg in Napier grass stems as opposed to 16.21 MJ/kg in leaves, combined, making 16.58 MJ/kg in stem and leaf, which indicates matured stands with tall stems will be a higher quality feedstock for bioenergy (Mohammed et al., 2015; Tsai and Tsai, 2016). The ratio of energy output to energy input is sometimes declared as 25:1 since it was confirmed that the heat of combustion of the biogas compounds was estimated to be 3.7-7.4 times higher than the heat required to pyrolyse Napier grass (Strezov, Evans and Hayman, 2008).

Napier grass with its vigorous development of biomass output was found to be a promising renewable energy source for different bioenergy fuels if it can be supplied steadily. On the one hand, it was confirmed that the Napier grass cultivars' chemical composition varied moderately but, on the other hand, the intercutting interval (maturity) had a substantial impact on their chemical composition (Ansah, Osafo and Hansen, 2010; Bayble, Melaku, and Prasad, 2007; Rengsirikul et al., 2013). As a result, matured stands of Napier grass crops which aim for a maximum yield of fresh biomass should be envisaged instead of cropping systems with short harvest intervals.

## 2.5 Sustainability and Cropping Systems

### 2.5.1 Environment and Agro-ecosystems

Humans use their environment and manipulate it- and life is affected by the environment, respectively-in other words, humans and the environment interact. Hence, the conservation of an intact environment including a rich biodiversity is of general interest and an important goal for today and future generations. Agrarian products are produced in ecosystems, so-called agro-ecosystems, counterbalanced by the multiple interests of environmental conservation, economics and anthroposphere (Perfecto et al., 1997). Generally, the agricultural industry builds one of the economically most important backbones of a nation. Farmers have had a direct influence on protection and sustainability since it has been focused particularly on agricultural systems during the last decades. Thus, environmental protection by sustainable agriculture systems became a politically important goal with economic and social aspects (Biala et al., 2007).

Arable farmland is the most basic unit of an agricultural system. It is won from an ecosystem, and transformed into an agro-ecosystem by land clearance. Furthermore, agro-ecosystems are characterized by a crop-farming system and management and, consequently, form the landscape and environment (Tscharntke et al., 2005). Environmental protection as well as sustainable agriculture became an interdisciplinary scientific field with various definitions, often ideologically defined, but often lacking practical implementations. Most often, the key issue of environmental protection by sustainable agriculture is considered if systems sustain themselves over a long period of time when they are economically viable, environmentally safe and socially fair (Lichtfouse et al., 2009). Agricultural systems are managed on local territories where, usually, stakeholders, local communities or national policies claim issues that aim for a sustainable development. As a consequence, national policies and local farmers, deny themselves quick profits and, rather, consider the needs of future generations (Rasul and Thapa, 2003).

### 2.5.2 Agricultural Systems

#### 2.5.2.1 Conventional Farming Systems

Contemporary agricultural systems for industrial field crops are optimized for efficiency and profitability by one high-yielding crop only which patterns standardized management. Through the whole cultivation process, from seed to harvest, management is done in the same pattern and monocultures obtain their full yield potential. Management changes natural to ideal conditions via additional irrigation in dry territories, chemical fertilization on less-fertile soils and chemical pest control to let crops develop without diseases (Rasul and Thapa, 2003). Location, field condition and climate define the ideal conditions which are met by a varyingly intense supplementation from external resources in order to enable best year-round agriculture. Heavy fertilization, chemical pest control and additional irrigation ensure highest yields and profitability but can easily become excessive depending on season and location (Dambroth and El Bassam, 1983). Cost reductions of supplemental inputs or low wages help to keep the price of the final product low and maximize profitability.

This industrial (conventional), farming system sharply increases yields but is counterbalanced by negative impacts on the environment, contrasting with the aims of sustainability (“over a long period of time under the vision of economically viable, environmentally safe and socially fair”) (Lichtfouse et al., 2009). Negative impacts on the environment by exploitive agriculture can be pollution, soil exhaustion, erosion, eutrophication, excessive water use and the development of weeds and diseases resistant to chemical control. Excessive fertilization, inefficient irrigation systems and unselective chemical pest control has accelerated the negative environmental impacts from industrial agriculture for profit (producing more and cheaper) but not dealing with future needs (Biala et al., 2007). Conventional farming systems, developed with the invention of chemical fertilizers, were intensified particularly after the Second World War for food production, later it led to solely economic profit through cheap production methods (Lichtfouse et al., 2009).

**2.5.2.2 Alternative Farming Systems**

Alternative farming systems grow mono-crops likewise in industrial patterns but under reduced inputs (low-input) and thus under less-than-ideal field conditions. The avoidance of drastically decreasing yields is thereby a great challenge (Singh et al., 2001). These farming systems envisage meeting sustainability by fulfillment of at least one or multiple visions of the key issues (economically viable, environmentally safe, socially fair and long-term use by protecting its productive resources) (Lichtfouse et al., 2009). To this aim, agro-ecosystems would be protected and would sustain agriculture for a long period of time.

However, less-than-ideal farming usually causes smaller yields along with economic and social aspects. Additionally, alternative agriculture systems are reliant on more management. Using the full spectrum of farming methods, namely management (i.e. rotational, alternative or season-adapted crops, green manure, agro-diversity), equipment (i.e. rainwater basins, highly-efficient equipment as drip irrigation, slow-release-fertilizers) and plant-endogenous characteristics (i.e.

environmentally tolerant crops, needs and availability, reduced fertilization needs by diazotrophic life or symbiotic nitrogen-fixing bacteria) help to keep alternative agriculture profitable (Barz and Delivand, 2011; Chainuvati and Athipanan, 2001). Most of these methods cannot replace resource deficits on the field but crops benefit indirectly from positive effects such as humification, increasing soil biota, natural phytosanitary potential, enrichment of crop diversity and maintenance of soil fertility by re-vitalizing soil flora and fauna by the reduction of chemical inputs as fertilizer or sprays (Rasul and Thapa, 2003). Between 20 to 40% of field based residues, remain as green manure on fields and are available as nutrients after the humification process for consecutive crops (Barz and Delivand, 2011).

Besides the conventional one, two alternative farming systems of reduced inputs are commonly found in Thailand (Elbersen and Andersen, 2008; Tancho, 2008):

1. Conventional (high-input): Manipulation to ideal conditions via supplementing field resources from deficit to optimum (heavy chemical fertilization, excessive irrigation).

2. Low-input: Low or reduced use of additional inputs as chemical fertilizers and/or irrigation leading to a cultivation of crops under less-than-ideal field conditions. Low-input farming management still is based on the principles of conventional farming but slightly adapted.

3. Natural: Tancho specifies in his work that the main concepts of natural farming are those of no tillage, no chemical fertilizers or herbicides. Plants should grow just as they do in naturally fertile forest soil (Tancho, 2013). In other words, crops are cultivated solely under field conditions (i.e. rainfed), exposed to

severe environmental stress (i.e. temporarily water stress by missing rainfall). In natural farming systems, very important management techniques such as the application of agro-chemicals, irrigation or weeding of concurrent plants are omitted completely, altering it fundamentally from the conventional system.

Conventional farming systems benefit from steady year-round yields and trusted crop quality even if they are counterbalanced by negative environmental effects. Alternative farming systems swap positive and negative effects of the conventional system. In other words, alternative farming systems preserve agro-ecosystems by processing the alternation's intensity from the conventional system but can risk yield security and crop quality (Lichtfouse et al., 2009).

**2.5.2.3 Future Expectations from Agricultural Systems**

Agricultural products will still ensure food security in the future under aspects of economics and society. In face of a growing world population and acreage limitation, existing farmland must be managed more intensely (more per unit) and more economically (more and cheaper) (Moore, 2008). Meeting these expectations, mono-cropping systems, not too fundamentally changed from the conventional system, must be able to bear high yields and protect agro-ecosystems for long-term production. Therefore, breeding programs investigate high-yielding crops by improving quantity and quality (Longpichai, 2013). Nevertheless, alternative farming systems for long-term farmland use will become more important because of their sustained protection of the environment and agro-ecosystem. Crop diversification and eco-adapted resource management prevent exploitation, keep fertility high and reduce phytosanitary infections (Chainuvati and Athipanan, 2001).

However, agriculture will not only be concentrating on food and fodder in the future. Energy from renewable sources such as biomass has already become a quite important branch of agriculture with a promising growing market potential through new technologies (Stöcker, 2008). Hence, many authors see the intensification of the land-use conflict which must be solved by the improvement of existing farmland or transformation of an estimated 2 Gha globally unused lands into agrarian use (Lemus and Lal, 2005). Thailand in particular, could approach acreage intensification by stress-tolerant energy crops and with the rotation of food crops instead of leaving farmland fallow during the dry season as seen in the Nakhon Ratchasima district of Thailand. The present investigation will examine whether Napier grass has a potential as a side, rotational, dry season or reclaiming crop and whether it could be grown for biomass for bio-energy in a multi-cropping system without the need for new acreage.

## 2.6 Thailand's Water Situation

It is estimated that, in the Northeast region, just 30% of cropping capacity is reached during the dry season under irrigation while un-irrigated fields lie completely fallow (Sethaputra et al., 2001; Topark-Ngarm and Gutteridge, 1986). Recently, drought stress has threatened all of Thailand, forcing the government to identify an Agricultural Crop Zoning System (ACZS), which separates Thailand into six zones and identifies the best water supply for six major crops. The ACZS is controversial for supporters and detractors (Pensupar, 2015; The Government Public Relations Department, 2016). Thus, Thailand already faces water deficiency and climate change is going to intensify droughts globally and regionally, requiring research for drought-tolerant crops and water saving farming practices (Quinn et al., 2015; Rao, Raghavendra and Reddy, 2006).

## 2.7 The Alternative Energy Development Plan

In 2013, the National Energy Policy Council introduced the 10-year Alternative Energy Development Plan (AEDP) to the public. Much waste and residue from agriculture, one of Thailand's most important economic sectors, are incurred as byproducts from field crops and can be used as one of various possible renewable energy sources. Utilized industrially, residues are proffering Thailand a promising opportunity to generate bioenergy from renewable feedstocks and, thus, to reduce of carbon dioxide emissions. Commercial biomass and waste-residue conversion via gasification in power plants requires costly industrial equipment in contrast to second-generation biofuel synthesis. Nonetheless, Napier grass as an energy crop is promoted by the AEDP as an additional and steady biomass source due to its double gas yield compared to other agricultural wastes as liquid manure (Amon et al., 2010). The AEDP raised the target of bio-electricity production of 10 MW from 10,000 rai (1,600 ha) in 2014, promoting Napier grass plantations to meet this target. Within 10 years, Napier grass plantations will be expanded onto 3 million rai (480,000 ha) producing 3,000 MW bio-electricity, CBG and LPG. Thus, crop planning and farming statistics are important for the estimation of all produced fuels (biomass and residues) needed for the dimension of power-plant capacity. The variations of physical and chemical composition of the raw biomass fuels determine whether biomass is suitable for existing conversion technology. Furthermore, the use of biomass fuels is based on conversion technology, cost effectiveness, supply security, environmental impacts and social issues (Barz and Delivand, 2011). Hence, the Ministry of Energy's Department of Alternative Energy Development and Efficiency (DEDE) expects a fixed 3,500 THB per rai and year (21,875 THB per ha and year) profit for farmers who joined in the project, since, that is more profitable than income from other crops (National Energy Policy Council, 2014).

## 2.8 The Gross Domestic Product and Thailand's Infrastructure

The latest domestic agricultural census of the National Statistical Office (NSO) amounted to a total acreage of 114.6 million rai (18.34 million ha) for Thailand in 2013. This area was owned by 5.9 million holdings, averaging 19.4 rai (3.10 ha) per holding. 2.8 million holders owned 46.7% of the total agrarian area (53.5 million rai) in the northeastern region, thus, forming the majority. In the Nakhon Ratchasima province there are 260,000 holders which is the highest number of holdings in the northeastern region. Thailand's farmers engaged in raising crops (96.4%) excluding other income activities (National Statistical Office, 2013).

Thailand's gross domestic product (GDP) amounted to 395,282 million US$ in 2015, placing Thailand as the 27$^{th}$ biggest national economy, employing 43% of its population in the agrarian sector (The World Bank, 2016). The agrarian sector accounted to 11.4% of the total GDP. Twenty million metric tonnes of rice, as the most important export product, was produced on 60% of the total acreage (Federal Ministry of Food and Agriculture, 2009).

Taken together, Thailand's infrastructure is based on a strong agrarian sector, which produces mainly food crops on 114.6 million rai. Most of the acreage is held by smallholders in the northeastern region, farming on an average of 19.4 rai. According to the AEDP in 2021, Napier grass shall be produced for biomass on 3 million rai (2.6% of current acreage). Supplying power plants with biomass requires continuous biomass production by a year-round single-crop, precluding agro-diversity. Power-plant logistics include structures of collective farming by smallholders, bringing opportunities for new incomes for many people.

## 2.9 Biomass Production from Napier Grass

### 2.9.1 Introduction

Napier grass has become a globally important industrial crop, raised for its fresh biomass, used for cattle fodder with production recently increased for conversion into energy. Thailand's infrastructure as well as its GDP offers favorable economic conditions to meet the 10-year AEDP and opens opportunities for new income for smallholders. For instance, producing biomass from Napier grass on Twain's 100,000 ha unused land, the environmental benefit of reducing $CO_2$ emissions and the economic benefits of oil-equivalent energy were calculated to be around $5.0 \times 10^6$ Gg/yr and $1.1 \times 10^7$ barrels/yr, respectively (Tsai and Tsai, 2016). Besides these benefits, Napier grass is a robust crop suitable for various environments on not very fertile land, limited only by soil compaction (Rahman et al., 2008; Williams, 1980).

### 2.9.2 Yield Productivity

The pioneers of Napier grass crops started cultivation due to its high yield potential, digestibility and further promising agronomic traits (Kennedy, 1919). Napier grass crops for fodder and milk production are economically still up-to-date and are promoted to smallholders in Thailand (Unknown, 2015). Nevertheless, recent perceptions on energy needs and advanced technical processes opened new markets for biomass. Its history provides enough experience for cropping in dairy or industrial systems and became almost standardized (Ferraris, 1980). Napier grass's chemical composition and structure, has made it attractive as a candidate for industrial conversion into energy (Dahiya, 2014). Regardless of the changed purpose, biomass quantity criteria remained very important and, thus, farming methods continued to be the same, yielding quantity and not quality as the economic determining factor. Experiment stations found yields ranging from 75-100 metric tonnes (= Mg) fresh mass per acre and year at 85-90% moisture content (equivalents 18.60 to 37.05 Mg DM $ha^{-1}$ $yr^{-1}$) under best farming conditions but just half of that under natural conditions in North America (Thompson, 1919; Wilsie and Takahashi, 1934). Optimized cropping concepts, high-yielding hybrids and varying soil fertility multiplies expectable yields nowadays (Bassam, 2010). Nevertheless, global, as well as regional, varying yields are shown in Figure 2.1. Pak Chong and Kon Khaen show a small regional difference even though the largest differences can be found globally. Currently, Napier grass's expected annual yield, depending on variety, ranges between 40 and 58 Mg DM $ha^{-1}$ (equivalents 6.4 and 9.28 Mg $rai^{-1}$) under conventional farming in Thailand (Rengsirikul et al., 2013).

Local environmental factors, farming practice as well as a variety's specific yield potential causes the wide range of yield in Figure 2.2. The AEDP promotes the Napier grass variety 'Pakchong 1', which can, potentially, yield 70-80 Mg FM $rai^{-1}$ $year^{-1}$ (equivalents 437.50-500 FM Mg $ha^{-1}$ $yr^{-1}$), calculating the capacity of power plant and acreage on half of the potential yield. However, long term investigations found total DM accumulations from 5-10 Mg $ha^{-1}$ $yr^{-1}$ in unfertilized swards and from

15-30 Mg ha$^{-1}$ yr$^{-1}$ in well fertilized pastures under realistic farm practices (Vermerris, 2008).

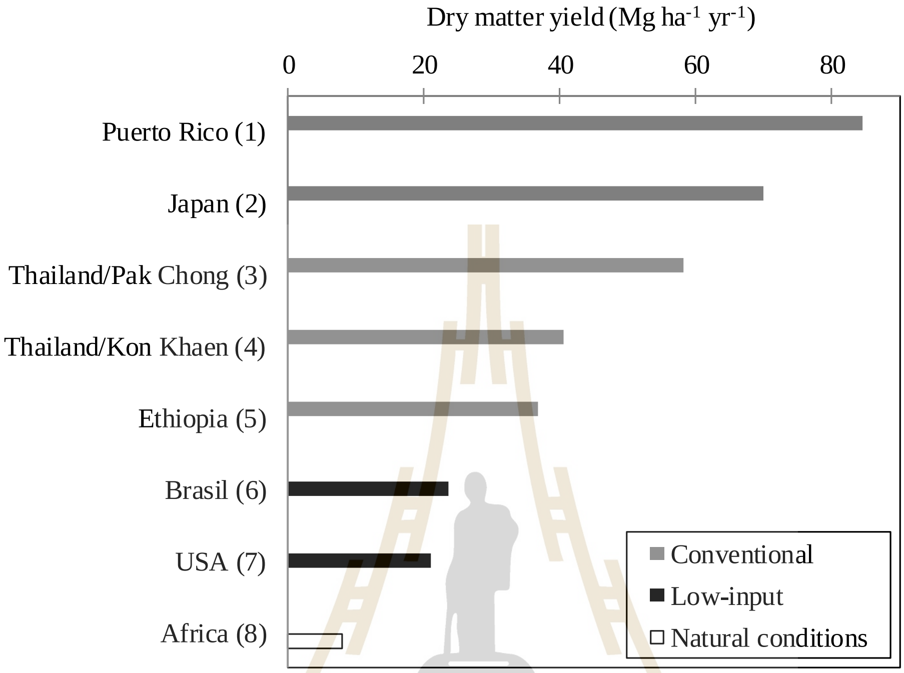



**Figure 2.2** DM yield of Napier grass considering production method and location. (1) (Vicente-Chandler, Silva, and Figarella, 1959), (2) (Miyagi, 1980), (3) (Rengsirikul et al., 2013), (4) (Wijitphan, Lorwilai, and Arkaseang, 2009b), (5) (Zewdu, 2008), (6) (de Morais et al., 2012), (7) (Knoll et al., 2011) and (8) (Ohimain, Kendabie, and Nwachukwu, 2014).

### 2.9.3 Turning Napier Grass into a Field Crop (from Plant to Crop)

Napier grass is grown predominantly in mono-cropping systems similar to that of sugarcane. Growing Napier grass as a fodder crop was already done for a long time by natives, before the yield potential was reported in the 19$^{th}$ century (Kennedy, 1919). Literature reports that the fodder value and crop potential had attracted the interest of E. G. Kenny and Colonel Napier, who called it to the attention of the Rhodesian Department of Agriculture, and started to grow it in one-crop systems. The common African names changed from Napier fodder to Napier grass, named after Colonel Napier, of Springs, Bulawayo. In other parts of Africa, settlers called it Elephant grass, a still widely used name (Stapf, 1912). At the same time Napier grass was spread to farmers in the whole of Africa who also started to farm it as crops (Burtt-Davy, 1915). In 1913, Napier grass was introduced to Florida and two years later in Hawaii as a pasture green-fodder crop for high yields (Thompson, 1919; Wilsie and Takahashi, 1934). At that time, Napier grass was already grown in mono-cropping systems under moderate fertilization. Recently cleared land and forests were the fields for cultivation. But there were too few canes for propagation available to meet the demand, thus, they started crops by generative propagation practices. The low requirements, as well as high yields on any type of land, led farmers to grow it under limited conditions as an almost natural crop. Yield increase under fertilization was observed and research on Napier grass crops became more specific (Paterson, 1933).

The investigation of industrial mono-crops started over a hundred years ago and has resulted in intensively researched and optimized production systems. However, the current land-use situation is changing and necessitates continuous investigation on production systems as arable land, in spite of the pioneer days in which Napier grass was preferentially planted on cleared land. Recent research fields focus on the intensification of land management which is subordinated into land use, yield maximization and sustainability under aspects of limited resource application. Interestingly, Wilsie and Takahashi found that different sett lengths for propagation demanded various levels of care (Wilsie and Takahashi, 1934). This report of the effects on the propagation material and the subsequent crop development, emphasizes that farmers can regulate resource management from propagation on. Then as now, cropping starts with vegetative propagation.

**2.9.4 Propagules and Field Propagation**

Four main parts of fresh biomass stalks (canes), joints (setts), ‘single eye’ cuttings (phytomers) and root clumps have been recommended as raw material for vegetative (asexual) propagation from the pioneer-days of Napier grass crops, (Briske, 1991; Thompson, 1919; Wilsie and Takahashi, 1934). Notwithstanding, propagation remained basically the same, as it still starts by planting propagules directly on the field. Root-clumps divisions have vanished as planting material in our time since far too much biomass is needed for them, while canes and setts are still popular for propagation. The planting of terminal cuttings, scarcely reported for industrial plantations, is another propagation-suitable part and method for tall grasses (Figure 2.3).

Interestingly, Napier grass crops have been, and still are, propagated by asexual stem sections, favoring regional preferences. On the one hand, canes of 3 to 5 feet (0.91 to 1.52 m), formerly recommended by Wilsie and Takahashi, are still preferred in North America. On the other hand, setts with 3 to 5 nodes (approximately 0.15 to 0.20 m) are favored in Thailand (Knoll et al., 2011; Lounglawan, Lounglawan and Suksombat, 2014). Setts bear a maximum number of plantlets from a limited number of canes. Although not recommended by Wilsie and Takahashi, due to failure under suboptimal conditions, planting of single-node cuttings (phytomers) has been recently promoted. The reason is that stalks can be efficiently divided into many phytomers, the smallest possible propagule (Knoll and Anderson, 2012; Treesat, 2010). Various long stem sections, burrowed into plowed-out furrows, will form good

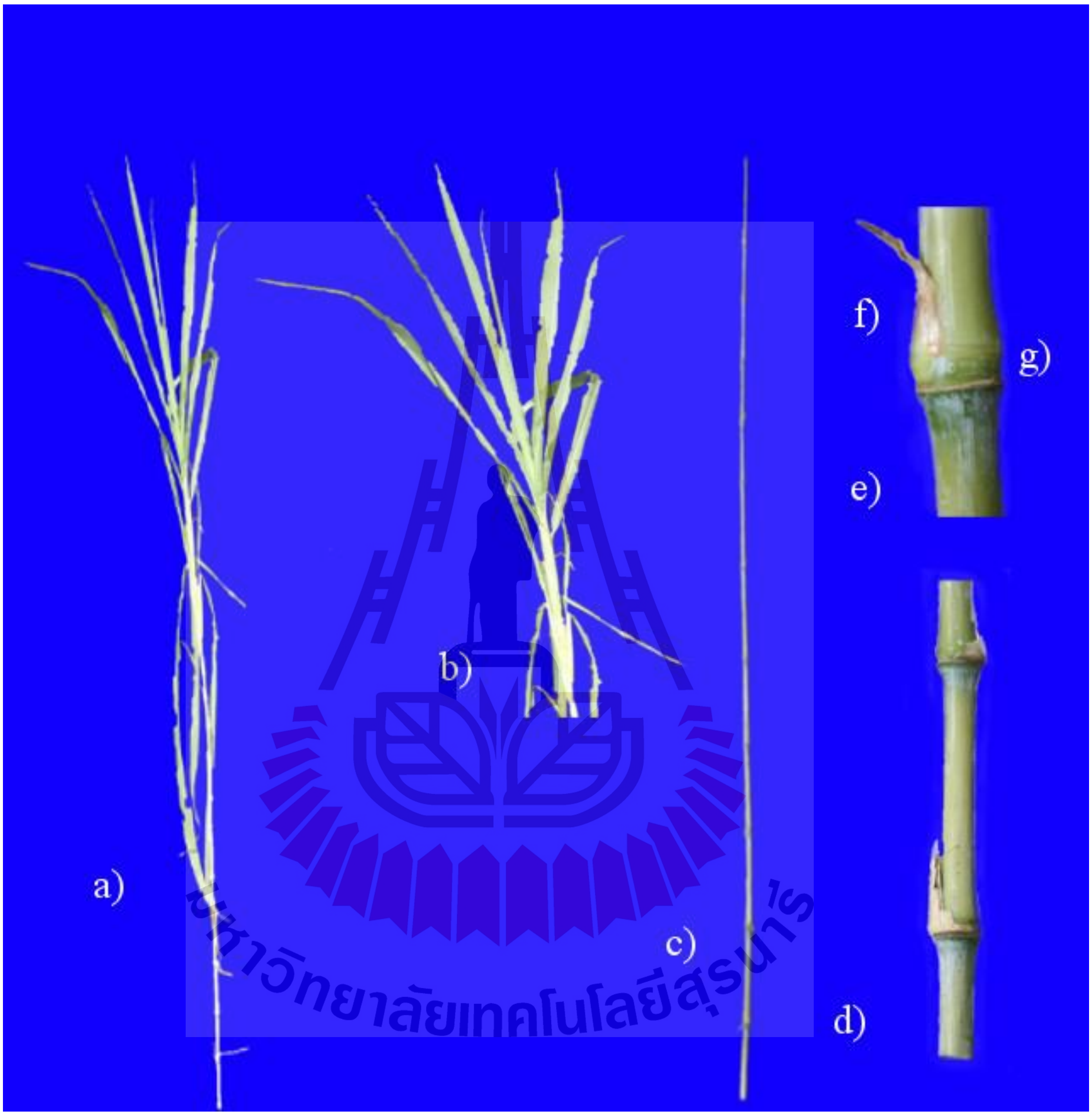



**Figure 2.3** Napier grass parts for asexual propagation. a) full stem, b) terminal cutting, c) cane (long stem section cutting), d) sett (short stem section cutting), e) phytomer (smallest unit for propagation) with one bud (f) and one node (g) (nodium) including growth ring, root band, leaf scar, root primordia.

stands with increasing lengths (Lounglawan, Lounglawan and Suksombat, 2014; Wilsie and Takahashi, 1934). Besides horizontal burying, setts can be inserted vertically for a better field handling. Planting by hand, which is commonly preferred in Thailand, brings the advantage of direct insertion of setts, instead of burrowing, being the faster working method. Direct sticking became prevalent since it exploited vigorous regeneration. At former times, just as today, the planting of seed canes (rooted liner plants) instead of in-field propagation is practiced where plantlets should be placed 2 feet (0.61 m) apart. Spacing has remained same with the density only doubled in Thailand, leading to high-yielding crops under supplemental irrigation as well as heavy fertilization (Tudsri et al., 2002; Wilsie and Takahashi, 1934). Due to regionally variable environmental conditions, local farming recommendations, are given for best cropping (Wijitphan, Lorwilai and Arkaseang, 2009a; Wijitphan, Lorwilai and Arkaseang et al., 2009b).

### 2.9.5 Vegetative Reproduction

Normally, Napier grass crops are asexually propagated by burying cane sections or vertical sticking with one node exposed (Knoll et al., 2011; Lounglawan, Lounglawan and Suksombat, 2014; Singh, Singh and Obeng, 2013). As every sett contains a single bud and a ring of root primordia, setts start root development from this primordia ring first, after which the bud breaks and begins to grow. The sprouting bud from the mother-cutting starts to develop many-clinched nodes and internodes before it breaks through the soil’s surface. The young tiller develops from the mother cutting until the sett roots perish after a couple of weeks and proceeds to root from its own nodes. This whole regrowth cycle lasts up to eight weeks (Bakker, 1999; Humbert, 1963). The reproduction cycle of cane-section cuttings is well researched in contrast to terminal cuttings as they are deemed un-rootable (Knoll and Anderson, 2012; Kolo et al., 2005). Most often, the upper bud of a vertically inserted sett starts to sprout and the basal primordia in the ground to build roots (shown on the right side of Figure 2.4). In contrast thereto, terminal cuttings turn into a plantlet and start to flush as soon as the basal primordia developed roots (shown on the left side of Figure 2.4).

**Figure 2.4** Regeneration stages of roots and shoots of two different cutting types of Napier grass. On the left, a terminal cutting with fresh shoots coming from apical nodes which are covered by leaf sheaths while the roots develop from the basal node. On the right, one sett with sett roots on the basal node and an apical flushing bud.

Napier grass's vigorous reproductive potential, where each bud can form a whole plant with a large tussock, results in fast regeneration that accounts for its popularity as a crop (Langer, 1979).

**2.9.6 Ecology**

Napier grass can grow naturally in almost all subtropical or tropical ecosystems - from swamps to arid environments-and is featured as a ruderal plant which colonizes primarily marginal or waste lands (Singh, Singh and Obeng, 2013). Meanwhile, Napier grass has been introduced into nearly all tropical and subtropical ecosystems where it sometimes has become a neophyte (Cutts et al., 2011). Its establishment in arid areas is aided by diazotrophic and thermophilic life, drought tolerance and a C4-photosynthesis. Particularly, C4-photosynthesis is found mostly in the subtropical and tropical belt with its geographical limitation in the temperate zone ($40^{th}$ latitude) due to a lower light intensity and a less efficient photorespiration rate (von Sengbusch, 1985). All tall grasses such as miscanthus, sugarcane or Napier grass, which invest in stem elongation during vegetative growth, have C4-photosynthesis (da Silva, Sbrissia and Pereira, 2015). The stems of tall grasses containing lignocellulose are, besides their fast biomass growth, attractive for bioenergy. Another name for Napier grass is elephant grass implying that it is a preferred forage evolutionarily adapted towards grazing and mechanically done as intercutting interval called ratooning. In nature and under farming management, Napier grass forms large tussocks of up to 60 tillers per tussock which bear high biomass yields (Langer, 1979). For insights into responses to grazing/ratooning mechanisms, stand development and plant architecture grasslands/crops are hierarchically organized (e.g. tiller, plant, population or community) (Briske, 1991).

### 2.9.7 Physiology and Stress Physiology

Wild-plant or crop environment is a stress factor for plant growth because exogenous biotic and abiotic factors cause stress. Biotic stress factors include infections, herbivory and competition while abiotic stress factors range from temperature, water, radiation to chemical, mechanical and other stress factors (Schulze, Beck and Hohenstein, 2005). Exogenous stress factors cause endogenous physiological adaptations which manifest themselves in morphological appearance as dwarf growth or increased lignin and fiber concentration as part of a faster maturity rate (Bayble, Melaku and Prasad, 2007; Morrison, 1980; Sarwar, 1999). Positive plant-stress effects can be useful for hardening as long as they cause no damage. However, pioneer plants as ruderal plants (for instance Napier grass) often have a stress-tolerant physiology or resistant-regulation mechanisms (Prasad, Staggenborg and Ristic, 2008). C4 plants with a high adaptation towards arid environments can utilize nutrients such as water more effectively than other photosynthetic life cycles (Ashraf and Harris, 2013). Water is the most regulating of vital processes and its availability limits natural plant colonization in ecosystems, or as an economic trait for crops, is intensified by climate change (Steduto et al., 2012). Napier grass shows high water-use efficiency (WUE), which lets crops grow under the roughest conditions (i.e. drought or heat). These traits (physiology and WUE) give Napier grass crops an advantage over competitive weeds.

### 2.9.8 Naturalization

Vegetative propagation material of Napier grass has become widely available with increasing cultivation, replacing seeds. Apart from formerly insufficient available setts during pioneer cropping, seeds are nowadays used only for hybridization (Thompson, 1919). Not noticed as a prospective problem in 1919, Napier grass naturalized and became an invasive plant in North America and other continents (Cutts et al., 2011). Napier grass, which is found wild or as a crop, was already introduced in Thailand in 1929 and has been widely cultivated with many local cultivars (Tudsri et al., 2002; Waramit and Chaugool, 2014). However, naturalization of existing crops must be prevented for the preservation of endemic flora with attention to Thailand's rich biodiversity.

# CHAPTER III

# MATERIAL AND METHODS

## 3.1 Experimental site

This study was conducted from 2012 to 2014 on a site located on the campus of Suranaree University of Technology (SUT), Nakhon Ratchasima Province, Thailand (LAT 14.87014° N, LON 102.03209° E, elevation 250 m). Due to chosen plot sizes, two neighboring fields were used for the experiment. Soil on both fields was classified as the Korat soil series (Oxic Paleustults) (Srisa-ard, 2007). Samples from the first 30 cm horizon were classified as humic acid sand by the VDLUFA-Method. Chemical and physical characteristics are shown in Table 3.1.

**Table 3.1 Physical and chemical soil characteristics of the experimental field site.**

| Sample | Soil type | pH-Value ($CaCl_2$) | Phosphorus (mg/kg) (CAL) | Potassium (mg/kg) (CAL) | Magnesium (mg/kg) ($CaCl_2$) | Composition (%) |
|---|---|---|---|---|---|---|
| Field one | humic sand | 5.6 | 20 (very low*) | 30 (low*) | 60 (high*) | 1.20 humus<br>3.90 clay<br>13.50 silt<br>82.60 sand |
| Field two | humic sand | 5.1 | 10 (very low*) | 20 (very low*) | 50 (optimum*) | 0.90 humus<br>3.70 clay<br>10.70 silt<br>85.60 sand |

* = categorized by the guidelines of the LWK Niedersachsen; Calcium acetate lactate extract (CAL).

The climate of the Nakhon Ratchasima Province belongs to the northeastern part of Thailand and possesses three seasons, rainy or southwest monsoon season (mid-May to mid-October), winter or northeast monsoon season (mid-October to mid-February) and the summer or pre-monsoon season (mid-February to mid-May). The average annual precipitation is around 1,200 mm and the average air temperature is 26.1°C, defined as tropical savanna (Meteorological Department, 2012; Kottek et al., 2006).

To monitor the environment during the study, a data logger (T-Warner, Type iMetos 2, Software Version 05.52, **Pessl Instruments GmbH,** Werksweg 107, 8160 Weiz, Austria) was installed close to the experimental site. The logger was equipped with sensors for measuring air temperature (SMT 160-30 with a convection cover) and precipitation (Joss-Tognini principle, Wilh. Lambrecht GmbH, Friedlaender Weg 65-67, 37085 Goettingen, Germany). Locally, cropping depends on monsoon rains and is therefore distinguished into rainy/growing (May to October) and dry/fallow (October to May) seasons. For this study, data of agrometeorological precipitation as well as minimum and maximum temperatures were recorded.



## 3.2 Experimental Design and Set-up

Normally, farming systems consist of four elementary farming practices: planting date, cutting type, initiation density and intercutting intervals which affect biomass production of Napier grass (Payne, 2000; Kolo et al., 2005; Ferraris, 1980; Tudsri et al., 2002). Hence, these treatments (T) were selected as being important for altering a farming system for Napier grass and were tested in a randomized block design. The experimental plots followed the recommended guidelines of the Federal

Plant Variety Office with each plot sized 6x14 m and spaced 1 m apart (BSA, 2000). All entries were replicated three times (Casler, Vermerris and Dixon, 2015).

Within the four main groups of treatments, variables were tested for specific effects in the tested natural farming system:

- T1: different initiation-sett densities (6, 9, 10 and 12 setts $m^{-2}$).
- T2: cutting type (15, 60 and 120 cm long canes and terminal cuttings).
- T3: intercutting intervals (4, 8 and 12-monthly).
- T4: regular and late planting (May, September).

Accordingly, effects of vertically inserted or horizontally buried setts were expected and investigated as well. Yield effects from increasing densities were also expected as from cane-section length and cutting type (stem section or terminal). Finally, an effect of late planting date (at the end of the rainy season in September) as well as from intercutting intervals was expected. Produced dry mass was used as the determinant of effects from tested variables. Taken together, seventeen specific entries were organized for the Napier grass cultivar from the SUT campus and tested in the experimental set-up from 2012-2014 (Table 3.2, Figure 3.1). Additionally, treatments and variables were tested with the cv. 'Pakchong' from 2013-2014 (Table 3.3). Napier grass-specific adaptions under natural conditions were observed and monitored for pre-selected entries in the years 2012-2014. The biometric performance was evaluated for seedling rate, tussock forming (=tiller per plant), tiller height and the photosynthetic-active leaf-area index (LAI).

**Table 3.2 Experimental set-up, treatments and attributes of the Napier grass cultivar from SUT campus for testing altered farming systems under natural conditions from 2012-2014.**

| Entry | Treatment | | | |
|---|---|---|---|---|
| | T1: plant density ($m^{-2}$) | T2: planting method (cutting type) | T5: intercutting regime ($yr^{-1}$) | T6: planting date |
| 1 | 6 | Horizontal (15 cm) | 1 | 17/05/12 (07/05/13) |
| 2 | 9 | Horizontal (15 cm) | 1 | 17/05/12 (07/05/13) |
| 3 | 12 | Horizontal (15 cm) | 1 | 17/05/12 (07/05/13) |
| 4 [E] | 10 | Horizontal (15 cm) | 1 | 17/05/12 (07/05/13) |
| 5 [E] | 9 | Horizontal (15 cm) | 3 | 17/05/12 |
| 6 [E] | 9 | Horizontal (15 cm) | 1 | 10/09/12 (05/12/13) |
| 7 [E] | 9 | Horizontal (15 cm) | 2 | 17/05/12 (07/05/13) |
| 8 | 9 | Terminal (Vertical) | 1 | 17/05/12 (07/05/13) |
| 9 [E] | 9 | Terminal (Vertical) | 3 | 17/05/12 (07/05/13) |
| 10 | 3 | Horizontal (60 cm) | 1 | 17/05/12 (07/05/13) |
| 11 [E] | 3 | Horizontal (60 cm) | 2 | 17/05/12 (07/05/13) |
| 12 | 3 | Horizontal (120 cm) | 1 | 17/05/12 (07/05/13) |
| 13 [E] | 3 | Horizontal (120 cm) | 2 | 17/05/12 (07/05/13) |
| 14 | 9 | Vertical (15 cm) | 1 | 17/05/12 (07/05/13) |
| 15 [E] | 9 | Vertical (15 cm) | 2 | 17/05/12 (07/05/13) |
| 16 [E] | 18 | Vertical (15 cm) | 2 | 17/05/12 (07/05/13) |
| 17 | 3 + 3 | Horizontal (60 cm) + Vertical (Terminal) | 3 | 17/05/12 (07/05/13) |

E = Evaluated for biometric performance. Inception dates of entries in replication experiment are parenthesized. * = size was reduced to 100 cm in the 2013/14 experiment.


Entry 1 with six horizontally laid 15 cm setts


Entry 2 with nine horizontally laid 15 cm setts


Entry 3 with twelve horizontally laid 15 cm setts


Entry 4 with ten horizontally laid 15 cm setts


Entry 14 with nine vertically inserted 15 cm setts


Entry 16 with eighteen vertically inserted 15 cm setts


Entry 10 with three horizontally laid 60 cm setts


Entry 8 with nine vertically inserted terminal cuttings

Entry 12 with three horizontally laid 120 cm setts

Entry 17 with three horizontally laid 60 cm setts and three terminal cuttings

**Figure 3.1 Planting patterns of entries consisting of different cutting types for the experiments from 2012-2014.**

**Table 3.3 Experimental set-up, treatments and attributes of the Napier grass cv. ˈPakchongˈ from SUT campus for testing altering farming systems under natural conditions from 2013-2014.**

| Entry | T1: cutting density ($m^{-2}$) | T2: planting method (cutting type) | T3: intercutting interval ($yr^{-1}$) | T4: inception (date) |
|---|---|---|---|---|
| 18 | 6 | Horizontal (15 cm) | 2 | 07/05/13 |
| 19 | 9 | Horizontal (15 cm) | 2 | 07/05/13 |
| 20 | 12 | Horizontal (15 cm) | 2 | 07/05/13 |
| 21 | 4 | Vertical (Terminal) | 2 | 07/05/13 |
| 22 | 3 | Horizontal (60 cm) | 2 | 07/05/13 |
| 23 | 4 | Vertical (15 cm) | 2 | 07/05/13 |
| 24 | 2 + 2 | Horizontal (60 cm) + Vertical (Terminal) | 2 | 07/05/13 |
| 25 | 2 | Horizontal (100 cm) | 2 | 07/05/13 |
| 26 | 1 | 45° (15 cm) | 2 | 07/05/13 |
| 27 | 2 | 45° (15 cm) | 2 | 07/05/13 |

Treatment: T1–T4



## 3.3 Cultivation Method

Regionally, Napier grass is cropped in the conventional farming system initiated by 15 cm setts inserted into the ground with one node exposed (Lounglawan, Lounglawan and Suksombat, 2014). Therefore, ripened canes are sized into sections as propagules for planting. Using this method, 15 cm setts were tested as smallest propagules in this experiment. Due to the non-uniform position on the coniform canes of Napier grass, to guarantee at least two nodes on each, the 15 cm setts were sized with a circular saw by hand, for larger sized setts, lengths-templates were used. The position on the cane affects regeneration of cutting, hence, both ends were removed for sizing (the basal end is very heavy with many clinched nodes while the terminal part opposes) and only the middle section of the cane was used. Before planting, sized propagules were selected for uniformity as well as minor variation of size, number of nodes and fresh mass weight (Tables 3.4 and 3.5).

**Table 3.4 Measurements of tested cutting types before planted in field in the experiment 2012.**

| | Cutting type | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 15 cm | | 60 cm | | 120 cm | | Terminal | |
| | (n = 201) | RSD (%) | (n = 100) | RSD (%) | (n = 100) | RSD (%) | (n = 46) | RSD (%) |
| Size (cm) | 16.73 ± 2.87 | 17.13 | 60.27 ± 2.40 | 3.99 | 121.2 ± 2.47 | 2.04 | | |
| FM (g) | 32.17 ± 17.00 | 52.85 | 133.59 ± 43.68 | 32.70 | 249.73 ± 93.28 | 37.35 | 87.11 ± 43.23 | 49.62 |
| Nodes (n) | 2.42 ± 0.71 | 29.34 | 6.87 ± 3.02 | 43.92 | 13.08 ± 5.44 | 41.56 | | |

**Table 3.5 Measurements of tested cutting types before planted in field in the experiment 2013.**

| | Cutting type | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 15 cm | | 60 cm | | 100 cm* | | Terminal | |
| | (n = 201) | RSD (%) | (n = 36) | RSD (%) | (n = 54) | RSD (%) | (n = 50) | RSD (%) |
| Size (cm) | 19.68 ± 2.44 | 12.40 | 64.19 ± 2.40 | 3.74 | 94.10 ± 5.71 | 6.06 | | |
| FM (g) | 31.96 ± 10.87 | 34.00 | 99.29 ± 29.71 | 29.92 | 155.63 ± 43.39 | 27.88 | 68.27 ± 3.59 | 37.21 |
| Nodes (n) | 2.02 ± 0.16 | 7.71 | 5.50 ± 1.06 | 19.19 | 6.74 ± 1.07 | 15.83 | | |

* = reduced to 100 cm due to limited propagation material in 2013.

Before the study was initiated, the fields were completely cleared and ploughed and the Napier grass cuttings were pruned of dry leaves. Subsequently, pursuant to entry-specific treatments (Tables 3.2 and 3.3), the cuttings were planted in triangular or grid patterns by hand. Setts, with two nodes, were treatment-specifically buried horizontally in furrows or inserted vertically with one node in the ground and the other node exposed. The terminal cuttings were inserted in the ground as deeply as possible but not deeper than their fresh leaf sheath.

The aerial biomass yield is an important parameter for Napier grass production. Napier grass is a grazing-tolerant plant and starts sprouting from basal buds after cut. Industrial biomass production manipulates the effect of grazing by rotational cuts (ratooning) which leaves the stubbles in the ground as they are found after natural grazing. Ratooning stimulates the tussock formation by tillers which results in a progressive biomass increase during the production. Stubble height after ratooning, intercutting intervals as well as the season affects re-growth from remaining stubbles by stimulation of basal buds. Contradictory research results show that the variety-specific effects of the cutting height, caused us to choose a 10 cm height in accordance with local practice (Butt et al., 1993; Jorgensen et al., 2010; Lounglawan, Lounglawan and Suksombat, 2014). Entry specific aerial biomass was manually cut with a brush cutter using the ratoon method, harvested, measured and subsequently analyzed. Plots were harvested in the same periodic intervals as scheduled in the set-ups (Tables 3.2 and 3.3). Following the natural farming concept, additional fertilization or irrigation, plant protection or weeding were omitted after planting or ratooning during the full study.

## 3.4 Determination of Plant Material

For the first and second experiment, cuttings were taken from a two-year-old abandoned Napier grass stand at the university farm. This Napier grass cultivar was unclassified therefore a herbarium voucher was prepared from one of the clones. It was transferred to the greenhouses at the Botanical Garden Munich for long-term documentation of the materials identity and deposited at the herbarium Ludwig-Maximilians-University Munich, Systematic Botany (MSB). The material was classified into species levels using traditional morphology-based keys along with a DNA barcoding approach. Total DNA was extracted from approx. 0.2 mg of fresh leaf tissue using the Macherey-Nagel NucleoSpin Plant Kit following the manufacturer's protocol. DNA was dissolved in a 50 µL elution buffer. After a check for quality and concentration on a 0.8% agarose-gel, 1 µL of template solution was used for PCR. Two regions are frequently used for molecular authentication of plant material, ITS (Internal transcribed spacer) from the nuclear ribosomal and trnL-F from the plastid DNA, and were chosen for the purpose of this study. Amplification was performed using the primer pairs leu1 and ITS 4 for ITS, C and F as described previously (White, Bruns, Lee, & Taylor, 1990; Taberlet, Gielly, Pautou, & Bouvet, 1991; C. Bräuchler, Meimberg, & Heubl, 2004; Christian Bräuchler, Meimberg, & Heubl, 2010). The PCR products were purified using the NucleoSpin Gel and PCR Clean up Kit (Macherey-Nagel, Düren, Germany) according to the manufacturer's protocol. The products were sequenced bidirectionally on an ABI PRISM 3730 (Applied Biosystems, Waltham, USA) automated DNA Analyzer at the LMU sequencing service.

For the third experiment, cuttings of the Napier grass's cultivar 'Pakchong' were bought from a local farmer.

## 3.5 Agronomic Parameter Analysis (Biometrical Performance Evaluation)

Competitive weeds, damaging insects and fungal infections were collected and vouchered for determination by literature during the full experimental period (Ho, 1999;

0 – 30%: Severe foliage damage with massive symptoms of decline

30 – 50%: More necrotic than phytosynthetic active foliage but still in a reversible condition

50 – 80%: Predominantly phototsynthetic active foliage with first signs of suboptimal development

80 – 100%: Optimal plant development by healthy aerial foliage and biomass

**Figure 3.2 Classification scheme for evaluation of photosynthetic active leaf area.**

Ratchalēt and Maxwell, 1994; Unknown, 2014). To monitor the agronomic performance of Napier grass stands in the natural farming system, pre-selected entries were evaluated before harvests (Table 3.2). Agronomic and biometric data were collected from all plants in the net plot. The product of node-input ($n_i$) (cutting-specific nodes (Tables 3.4 and 3.5)) was calculated from the number of cuttings per square meter or the planting method (Tables 3.2 and 3.3). Subsequently, the counted number of growing buds ($b_g$) was calculated as $S_r$ (%) = ($b_g$ / $n_i$) x 100. Plant tillers were counted individually and their aerial height (from ground to apical meristem) was measured with a tapeline and averaged. The attached trash (t) and leaf damage (d) (caused by *Curvularia penniseti*, *Cladosporium* spec. and *Myllocerus subfasciatus* Guérin-Méneville (Table 4.1) (Farrell, Simons and Hillocks, 2002; Hill, 2008)) was recorded in decimal steps from 0 to 100 per plant and expressed as percent (Figure 3.2). The photosynthetic-active leaf-area index (LAI) was calculated as LAI (%) = $(100 - (\sum (t + d)/n)) \times 100$.

## 3.6 Plant Sampling and Data Analysis

For sampling, the aerial biomass of the full plot (6x14 m) was harvested (10 cm above ground) with the ratoon method and the stubbles remained in the ground for sprouting. Above-ground harvested biomass was completely removed from plots and only the yield of the net plot (2x6 m) was analyzed. Fresh mass (FM) was weighed and 200 g of the individual samples were oven-dried at 80°C for 72 h to a constant weight and dry mass (DM) was determined. Moisture content of samples (MC) was calculated as MC = (FM – DM) / FM (as percentage x 100) and averaged (Av. MC) per harvest. The sample's DM for the net plot was converted to DM = FM (1–Av. MC) x (5/6) and expressed as Mg $ha^{-1}$ for ANOVA.

## 3.7 Statistical Analysis

The DM yields of entries were statistically compared for significances. Data collected for various comparisons were subjected to the analysis of variance (ANOVA) appropriate to the design as given by Munzert (Munzert, 1992). All statistical data analysis were performed using the IBM SPSS Statistics for Windows, Version 23.0 (IBM Corp., 2015). The LSD-test was used to determine significant differences between treatment. The significant differences between treatments were compared with the critical difference at 0.05 levels of probability for significance.

# CHAPTER IV

# RESULTS AND DISCUSSIONS

## 4.1 Plant Material

Various cultivars of Napier grass with different agronomic characteristics were raised from breeding programs (van de Wouw, Hanson and Luethi, 1999; Wanjala et al., 2013). Plant development and agricultural performance of cultivars can be quite variable and make a determination of the plant material necessary (Rengsirikul et al., 2013; van de Wouw, Hanson and Luethi, 1999). For the unknown Napier grass cultivar from the SUT farm, a phylogenetic determination was conducted. The resulting consensus sequences (GenBank Accession numbers: KR350689, KR350690) were checked for identity using BLAST with the top scores (100% coverage, 99% sequence identity) being two accessions of *Pennisetum purpureum* (JX156340.1, JX156338.1) confirming morphological determination (Zhang et al., 2000).

## 4.2 Competitive Weeds and Pests

Napier grass counts as a vigorous growing crop. Nevertheless, competitive weeds can affect stands by overgrowing (Aldrich, 1984). For best yields, crops profit from full sunlight, whereas shade from competitive weeds or dense interrows reduce sunlight and thus biomass yield, respectively (Nagasuga, 2005). Usually, weeds overgrow Napier grass stands quickly after planting as long as the propagules are not flushing. With sprouting buds, approximately 3 weeks after planting, the quickly developing plantlets cover the soil surface and suppress competitive weeds naturally. With successive development, Napier grass forms large lateral tussocks and supresses competitive weeds completely (Pereira et al., 2015). Basically, competitive weeds are classified in two main groups which are either dispersed by seed or root. Twenty-four seed-dispersed and no-root weeds were identified during the full experimental period (Table 4.1). Hence, weeds compete with Napier grass stands in the time after planting. Particularly in the experiment from 2012-2013, Napier grass was observed to form sparse stands and competitive weeds were able to overgrow crops. Additionally, it was noticed that crops profited from intercutting intervals as crops were able to recover and competitive weeds died off. At the end of the rainy season, in contrast to the crops, seed-dispersed weeds died off naturally.

Occasionally, three weeds (*Imperata cylindrica*, *Pennisetum polystachion* and *Hyptis suaveolens*) competed most strongly with Napier grass crops. *Hyptis suaveolens*, dispersed by seed, occurred from May until September before it died off naturally. *Imperata cylindrica* and *Pennisetum polystachion*, closely related to Napier grass in the sweet-grass family, occurred partially on plots and formed dense stands with large tussocks (up to 80 cm in diameter) which suppressed crops. Most competitive weeds were removed automatically by ratooning or by developing Napier grass architecture except for *Imperata cylindrica* and *Pennisetum polystachion*. Interestingly, stands, planted from terminal cuttings (i.e. entry 9), covered the surface a short time after rooting and overgrew competitive weeds quickly. Terminal cuttings were evaluated for significant apical growth, disregarding tussock formation (Table 4.8), and thus, it was observed that by a planting density of 9 cuttings per square meter the soil’s surface was covered. At the end of the experiments, almost no competitive weeds were observed in plots of terminal cuttings, similar to those found in conventional managed crops. An increasingly competitive weed density was observed in plots with loose stands of Napier grass crops that also produced little yield (Table 4.6).

**Table 4.1 Competitive weeds on Napier grass fields, sorted by competitiveness.**

| Family | Genus | Species |
|---|---|---|
| *Gramineae* | *Pennisetum* | *polystachion* (L.) Schult. |
| *Gramineae* | *Imperata* | *cylindrica* (L.) Raeusch. |
| *Lamiaceae* | *Hyptis* | *suaveolens* (L.) Poit. |
| *Leguminosae* | *Tephrosia* | *vestita* Vogel |
| *Passifloraceae* | *Passiflora* | *foetida* L. |
| *Asclepiadaceae* | *Streptocaulon* | *juventas* (Lour.) Merr. |
| *Compositae* | *Bidens* | *pilosa* var. *minor* (Blume) Sherff |
| *Compositae* | *Tridax* | *procumbens* (L.) L. |
| *Cyperaceae* | *Fimbristylis* | *dichotoma* (L.) Vahl. |
| *Cyperaceae* | *Cyperus* | *compressus* L. |
| *Euphorbiaceae* | *Microstachys* | *chamaelea* (L.) Müll.Arg. |
| *Gramineae* | *Dactyloctenium* | *aegyptium* (L.) Willd. |
| *Leguminosae* | *Alysicarpus* | *vaginalis* L. DC. |
| *Leguminosae* | *Crotalaria* | *pallida* Aiton |
| *Leguminosae* | *Uraria* | *lagopodioides* (L.) DC. |
| *Leguminosae* | *Dunbaria* | *rotundifolia* (Lour.) Merr. |
| *Legumiosae* | *Indigofera* | *hirsuta* L. |
| *Malvaceae* | *Urena* | *lobata* L. |
| *Malvaceae* | *Sida* | *cordifolia* L. |
| *Polygonaceae* | *Polygonum* | *persicaria* L. |
| *Rubiaceae* | *Richardia* | *brasiliensis* Gomes |
| *Rubiaceae* | *Mitracarpus* | *villosus* (Sw.) DC. |
| *Sterculiaceae* | *Melochia* | *corchorifolia* L. |
| *Verbenaceae* | *Lantana* | *camara* L. |

In summary, Napier grass crops were able to produce biomass yields under natural conditions (omitted weeding) and tested management practices. Seed-dispersed weeds occurred temporarily and were subsequently overgrown by crops. Competitive grasses caused massive problems that cannot be ignored and had to be weeded mechanically. With increasing rooting rates, stands formed more densely and suppressed weeds automatically. It was observed that seedling rates of 20% were sufficient to cover soil surface quickly, suppressed competitive weeds consequently and produced biomass without weed management. For instance, nine terminal cuttings per square meter can be recommended as an environmentally friendly strategy for the reduction of production costs by omitted weed management (Hakansson, 2003).

In addition to competitive weeds, pests also cause economic crop damages. Pest attacks depend on favorable ecological factors which can occur during the whole production process. Pest populations can become epidemic due to the short reproduction cycle under favorable ecological conditions and cause considerable biomass reduction within the life cycle (feeding and hosting) as well as the crop's debilitation by the reduction of photosynthetic active leaf area (Farrell, Simons and Hillocks, 2002; Hill, 2008). Pests are classified into crop-host specific and non-specific life.

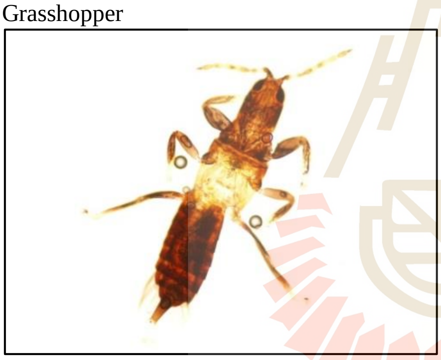
Napier grass is a crop with few specific infections making chemical pest spraying unnecessary which is important for forage production. However, polyphagous insects or non-specific infections can also cause massive damages to Napier grass crops. Hence, crops must be monitored constantly during the whole cropping period. During the full experimental period, diverse pests and infections were monitored, as shown in Table 4.2, and leaf-area reduction was included in the biometric evaluation.

Pest populations, determined by the level of disorders, need to be controlled by management activities such as the application of chemical spray. Tolerable leaf bites by weevils appeared during the whole experimental period together with died-off stem section parts which were caused by stem borers. Larvae activity was observed particularly during the dry season. Weevils (*Myllocerus subfasciatus*) usually host on vegetable crops and cause leaf-area reduction by notching leaf edges. Chemical pest management against weevils is environmentally critical as spray components also affect multiple harmless or useful insects as well (Dent et al., 1995). Stemborers' larvae tunnel inside stem sections bordered by nodes, and cause die-off of upper stem parts. Control is difficult due to their hidden life cycle, making the adult insects the attacking stage. The beginnings of attack are difficult to recognize, and mostly too late, with the appearance of died-off plant parts and also too late for consequent adult-insect control. Rotational harvests remove biomass and reduce stemborer populations automatically while long cropping periods without intercutting intervals foster growing pest populations (Tan, 2015). Meeting the sustainable goal of natural farming, the application of pest sprays was omitted completely for the full experimental period as damages appeared periodically on a tolerable level.

## 4.3 Weather at the Study Site

In Thailand, cropping depends on monsoon rains and is, therefore, divided into rainy/growing (May to October) and dry/fallow (October to May) seasons. Figure 4.1, summarized on a monthly interval, was clearly congruent with these two seasons, January. In May 2013 and 2014, the dry season ended and the rainy season started more intensely with heavier rainfall than in 2012. Moderate average temperature proceeded

**Table 4.2 Pest and disease causing disorders monitored during the experiment.**

| Pest | Description of damage cause |
|---|---|
|  Weevil (*Myllocerus subfasciatus* Guérin-Méneville) | Adult weevils feed by notching typical V-shapes on foliage margins, host usually on vegetable crops. |
|  Grasshopper | Grasshoppers are non-specific hosting on plants by notching full intercostal leave areas. |
|  Adult Thrips | Larval and adult thrips puncture plant surface and feed on the sap that is exuded from the resulting wounds. The damage appears as white or silver speckles, can easily be mistaken for nitrogen-fixing bacteria commonly found in Napier grass's leaves. |
|  Stemborer | Stemborers are any insect larva that bores into plant stems, where larvae start to host from inside fibres that are bordered by nodes. Upper-plant parts die off due to disturbed metabolism. |
|  Fungal leaf infection by *Curvularia penniseti* and *Cladosporium* spec. | Typical round-to-ovate-shaped leaf spot disease with partial leaf necrosis randomly found on the leaf blade. |

having a maximum peak of rainfall in September and a pronounced dry season in between 21.81°C (January 2014) and 28.77°C (April 2013) during the full experimental period, which was most favorable for thermophilic Napier grass. The temperature decreased continuously during the dry seasons, reaching lowest values in the middle of the dry season, and increased again before the rainy season started (Figure 4.1). In conclusion, the rainy season was warmer than the dry season and, thus, was the more favorable time for crops.

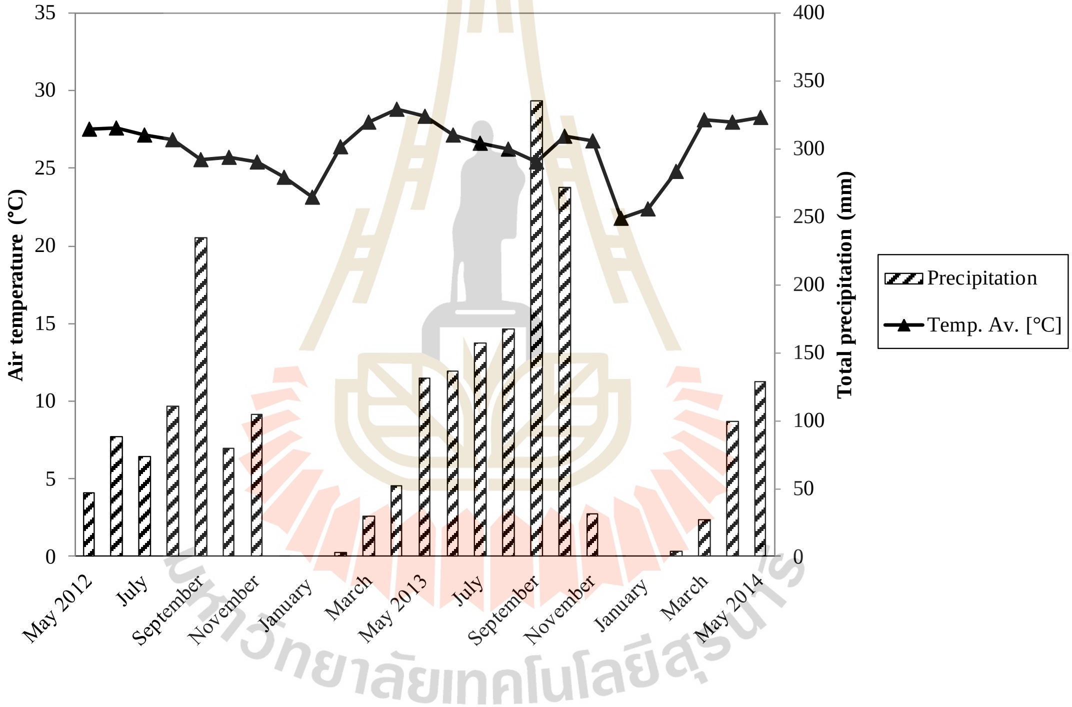



**Figure 4.1 Monthly precipitation and average temperature for the duration of the field experiments at SUT; data obtained from the field site.**

The precipitation ranged between 0.00 and 233.00 mm during the first study and 0.00 and 335.00 mm during the second and third studies. A total rainfall of 811.40 mm was measured for the first study (2012-2013) and 1351.70 mm for the second and third studies (2013-2014). Particularly, the rainfall in September and October 2013 was part of a higher annual total precipitation and flooded all experimental plots temporarily until November 2013. Figure 4.1 mirrors the course of the rainy season from May until November with a precipitation peak in September. The dry season was characterized by almost no rainfall from December until March and ended with light rainfall in March. In summary, the temperature and precipitation during the rainy seasons were most favorable for cropping as it is principally done in the Nakhon Ratchasima Province.

Water supply from additional irrigation after in-field propagation supports fast and best rooting as is commonly practiced in Thailand for Napier grass crop initiation. Setts under supplemental irrigation take root easily and uniformly within one or two weeks. Inhomogeneous or complete rooting failure is caused by increasing deficit intensity that affects produced biomass yields. Hence, the best germination correlates directly with high biomass yields and yield failure is a sign of rooting failure (Johl, 1979). Unpredictable water supply under rainfed management and during the time directly after planting, exposes propagules to environmental conditions and determines the quality of rooting (from failure to inhomogeneous, to best) as well as the expectable biomass and yield quality (Vangnai, 1981; Veenendaal et al., 1996). The annual rainfall of 811 mm during the investigation lay two-thirds under the regional long-term average in this study (Meteorological Department, 2012). Nevertheless, rainfall was sufficient for successful germination and all plots developed plantlets but DM yields and evaluation showed inhomogeneous root taking (Figure 4.3 and Table 4.8).

## 4.4 First Experiment (07/05/2012 until 27/04/2013)

Accumulated dry mass (DM) in relation to cutting type and precipitation is shown in Figure 4.2. DM yields of 15 cm setts varied marginally and the chart line proceeds almost parallel despite the planting method (vertical or horizontal). Yields of both cutting types increased perceivably when 800 mm rainfall was consumed, whereas yields of vertically planted setts surpassed horizontal ones. Cane sections of 60 and 120 cm also produced little accumulated DM but the chart lines have a higher base level. To this end, chart lines of all cane sett types are close together with moderate spreads. Obviously, the chart line of terminal cuttings appears almost linear and signals the close correlation between DM and precipitation. This finding is attributed to the effect of biomass growth from photosynthesis, hence, terminal cuttings developed more quickly than cane section and, thus, used precipitation, which increased with time, more efficiently. This is very consistent with the observation that terminal cuttings started sprouting already five days after planting in field. In contrast, the process of bud germination (from bud to plantlet) of stem sections is described as lasting up to eight weeks (Bakker, 1999; Humbert, 1963). Consistent with present observation, it is reported in literature that softwood plum cuttings from terminal shoots rooted and flushed more quickly than more-lignified lateral shoots (Hartmann et al., 2013).

Finally, produced dry mass (DM) ranged from roughly 0.6 to 16 Mg DM ha$^{-1}$ (Figure 4.3). Bar charts include the standard deviation of mean DM and increase spreads parallel to increasing yield. The DM yield of entry 8 (roughly 16 Mg DM ha$^{-1}$) stood out from the others. Interestingly, most of the sett-containing entries ranged below a yield of 2 Mg DM ha$^{-1}$, in contrast to yields from long-stem sections or terminal cuttings which obviously produced more biomass. In the present investigation produced yields are lower than from heavily fertilized and irrigated plots which range between 40-60 Mg DM ha$^{-1}$ (Rengsirikul et al., 2013; Wijitphan, Lorwilai and Arkaseang, 2009b). In other studies in which fertility was more limited, Napier grass averaged 26.3, 20.9 and 9.8 Mg DM ha$^{-1}$ in three successive harvests with no application of N-fertilizer (de Morais et al., 2009). However, yields of many entries remain even lower than reported from naturalized Napier grass which yielded between 7 and 11 Mg DM ha$^{-1}$ (Ohimain, Kendabie and Nwachukwu, 2014).

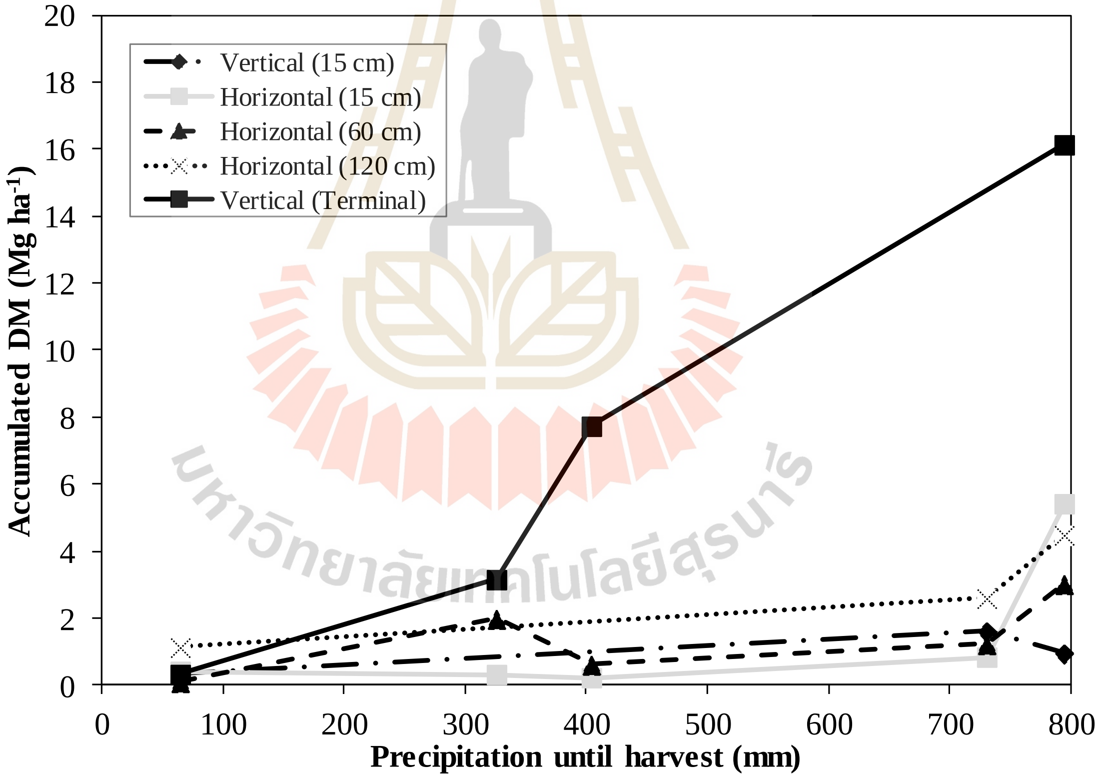



**Figure 4.2** **Produced biomass from cutting types in response to quantities of consumed rainfall; yields and precipitation accumulated for intercutting intervals.**

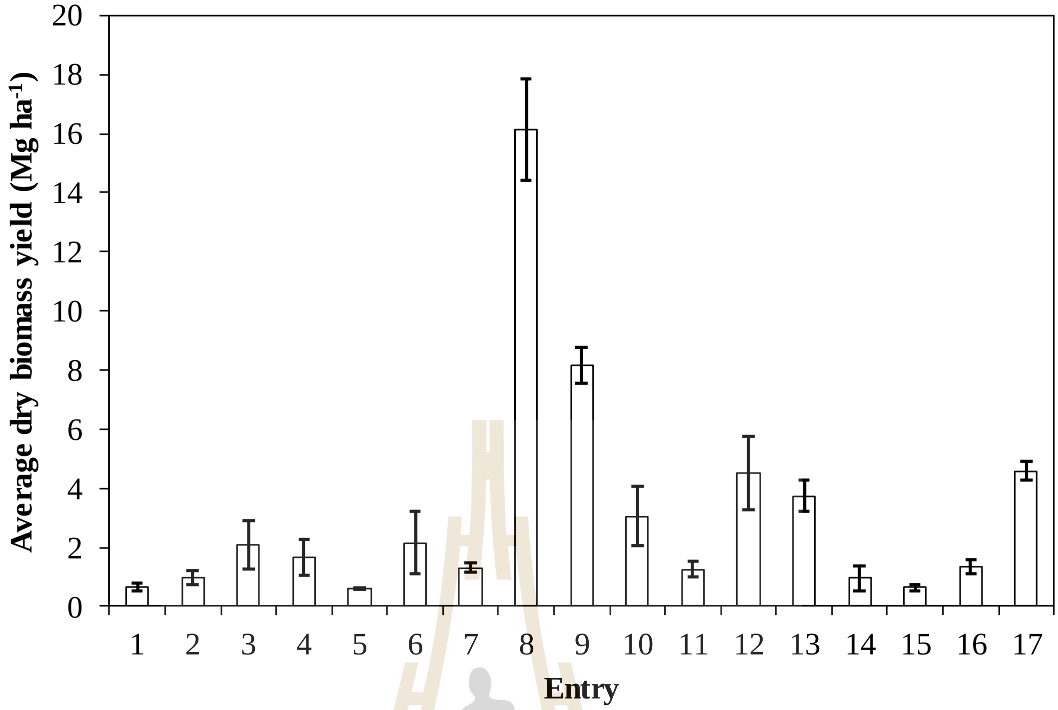



**Figure 4.3 Distribution of dry-mass yields and specific standard deviation of entries of Napier grass after completion of the study from 2012 to 2013.**

In Figure 4.3, yields of ratooned and non-ratooned equivalents (entries 2/5, 10/11, 12/13 and 14/15) clearly visualize a negative impact of ratooning on entries which produced less biomass in consequence. Due to frequent intercutting intervals, particularly entries 5 and 15 evinced consistently small yields. From inception to cessation, small yields revealed a poor development of stands exacerbated by ratooning. Measured yields from 60 cm (10/11) and 120 cm (12/13) long cane sections together with cane/terminal mixed entry 17 ranged on a middle level of all yields albeit ratooning during dry season caused an immense yield drop as well (Figure 4.4). Clearly, most biomass was produced by entries consisting of terminal cuttings, entry 8 yielded the highest (16 Mg DM $ha^{-1}$) followed by two-times-ratooned entry 9 with

8.16 Mg DM ha$^{-1}$. After four months, entries 5, 9 and 17 were harvested for the first time and statistical differences were found, shown in Table 4.3.

**Table 4.3 Effect of cutting type on dry mass on a four-monthly intercutting interval in the experimental period 2012 to 2013.**

| | | Mg DM ha$^{-1}$ | | |
|---|---|---|---|---|
| | | Intercut | | |
| | Cutting type | 10/09/2012 | 07/01/2013 | 27/04/2013 |
| | Av. MC (%) | 70.06 | 47.84 | 59.37 |
| Entry 5 | (Horizontal 15 cm) | 0.19 c, A | 0.31 b, A | 0.11 a, B |
| Entry 9 | (Terminal) | 5.86 a, A | 1.99 a, B | 0.31 a, C |
| Entry 17 | (60 cm + terminal) | 2.54 b, A | 1.95 a, A | 0.09 a, B |

Means followed by the same lowercase letter within a column and the same uppercase letter within a row are not significantly different. Av. MC = Average moisture content.

Entry 5 yielded with 0.19 Mg DM ha$^{-1}$ the least at the first interval and significantly less than entries 9 and 17 (5.86 and 2.54 Mg DM ha$^{-1}$). Interestingly, the different cutting types which were used for planting entries, bore a biomass decline from unmixed terminal cuttings (entry 9) to 60 cm stem sections + terminal cuttings (entry 17) to 15 cm (entry 5) setts. After eight months, yields of entries 9 and 17 were more or less on same level and differed significantly from entry 5. Entry 9 showed a severe yield drop from 5.86 to 1.99 Mg DM ha$^{-1}$ after ratooning in September. After twelve months, yields of all entries simultaneously decreased on an insignificant level and ascertained a negative impact of ratooning, particularly during the dry season, as previous ratoons did not show such a drastic decrease (Figure 4.4). In conclusion, entries yielded significantly less with successive intercutting intervals and produced, finally, no biomass (0.09 to 0.31 Mg DM ha$^{-1}$) on that occasion (Table 4.3).

Excessively frequent intercutting intervals and ratooning in the dry season led to massive crop damages and yield failure.

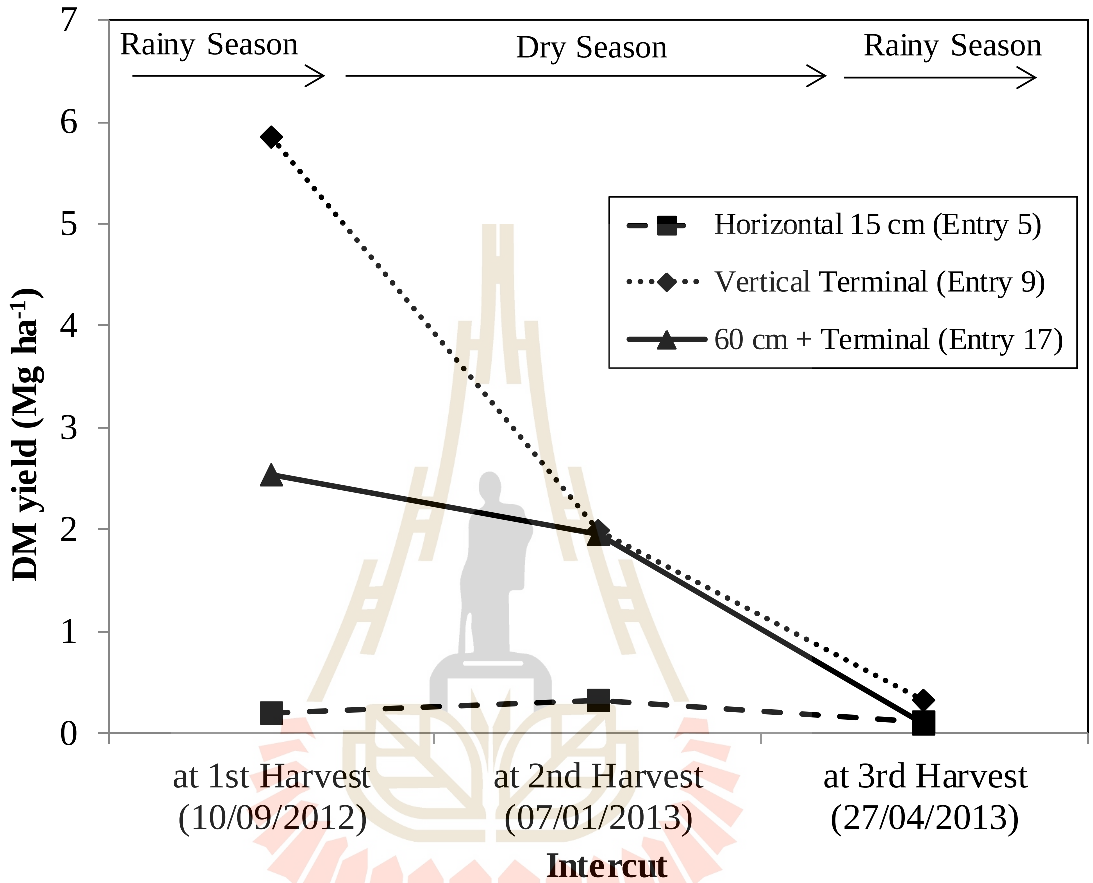



**Figure 4.4** **Yield response on intercutting interval and season.**

After harvest in January, biomass of stem sections with varying length yielded a wide range from 0.54 to 2.60 Mg DM $ha^{-1}$, shown in Table 4.4. The DM yields differed insignificantly on that occasion and showed no significant effect on stem-section length (entries 7, 11 and 13) or vertical or horizontal planting method of setts (entries 7, 15 and 16). Additionally, no significant effect was found between entries 15 and 16, although entry 16 was planted with twice as many propagules. Nevertheless, a tendency toward yield improvement with increasing length of stem section (from 60 to

120 cm, entries 11 and 13) or double planting density (entries 15 and 16) was found. Interestingly, with the propagation method, horizontal or vertical insertion (entries 7 and 16), yield doubled also. Primordia of Napier grass start asexual regeneration by taking roots on the sett. The regeneration activity remains without interaction or translocation effects in the phytomer section and, as a result, aerial buds often shrivel and are not part of the reproduction physiology. Hence, only buried buds regenerated and double nodes in the ground bore, consequently, double biomass, i.e. from double cane length (60 to 120 cm) or planting method (vertical or horizontal) of setts. A previous investigation described that higher planting densities also increased yields, hence, higher yields from increased nodes in the ground is generally consistent with this report (Wijitphan, Lorwilai and Arkaseang, 2009b).

**Table 4.4 Effect of stem-section length and planting method on DM at two different harvesting dates in the experimental period 2012 to 2013.**

| | | Mg DM ha$^{-1}$ | |
|---|---|---|---|
| | | Intercut | |
| | Cutting type | 07/01/2013 | 27/04/2013 |
| Entry 7 | (Horizontal 15 cm) | 1.01 a, A | 0.31 a, A |
| Entry 11 | (Horizontal 60 cm) | 1.22 a, A | 0.04 a, A |
| Entry 13 | (Horizontal 120 cm) | 2.60 a, A | 1.14 a, A |
| Entry 15 | (Vertical 15 cm) | 0.54 a, A | 0.10 a, A |
| Entry 16 | (Vertical 15 cm) | 1.09 a, A | 0.26 a, A |

Means followed by the same lowercase letter within a column and the same uppercase letter within a row are not significantly different.

At the second intercutting interval, the biomass of all entries (Table 4.4) decreased massively, even though not statistically significantly, and ranged between

0.04 to 1.14 Mg DM ha$^{-1}$. Particularly, entry 11 (60 cm sized stem section) decreased to an almost immeasurably low biomass yield (0.04 Mg DM ha$^{-1}$) after ratooning and signals shrinkage from a vital crop; close to a total crop loss. Nevertheless, besides a drastic biomass decrease, ratooning showed no significant effect on setts which contradicts a previous investigation in which a negative impact of intercutting during the dry season was reported (Tudsri et al., 2002).

After a cropping period of twelve months, the biomass of non-ratooned entries, shown in Table 4.5, was harvested. The biomass yields ranged between 0.96 to 16.14 Mg DM ha$^{-1}$ with a significant yield difference from entry 8 (16.14 Mg DM ha$^{-1}$) that was planted with terminal cuttings. The outstanding biomass of entry 8 resulted from a dense established stand with an estimated hundred percent seedling rate.

**Table 4.5 Effect of intercuts and cutting type on dry mass in the experimental period 2012 to 2013. Yield of ratooned entries was accumulated.**

| | | Mg DM ha$^{-1}$ | |
|---|---|---|---|
| Cutting type | Comparison | Intercut | Uninterrupted |
| (Horizontal 15 cm) | Entry 5 / Entry 2 | 0.61 b, A | 0.96 b, A |
| (Terminal) | Entry 9 / Entry 8 | 8.16 a, B | 16.14 a, A |
| (Horizontal 60 cm) | Entry 11 / Entry 10 | 1.26 b, A | 3.05 b, A |
| (Horizontal 120 cm) | Entry 13 / Entry 12 | 3.74 b, A | 4.51 b, A |
| (Vertical 15 cm) | Entry 15 / Entry 14 | 0.64 b, A | 0.96 b, A |

Means followed by the same lowercase letter within a column and the same uppercase letter within a row are not significantly different.

Accumulated yields of ratooned entries ranged between 0.61 and 8.16 Mg ha$^{-1}$ whereas 15 cm setts (entries 5 and 15, 0.61 and 0.64 Mg DM ha$^{-1}$) yielded the least (Table 4.5). In a statistical comparison, the biomass of entry 9 (8.16 Mg DM ha$^{-1}$), which was planted solely with terminal cuttings, differed significantly from other entries.

Generally, entries which grew uninterrupted produced more biomass than ratooned equivalents in the present experiment. At the same time, stem sections with increasing length, entries 10 and 12 (60 cm and 120 cm), produced more biomass (3.05 and 4.51 Mg DM $ha^{-1}$) than the smaller 15 cm setts (entries 2 and 14 produced 0.96 Mg DM $ha^{-1}$). Nevertheless, all their biomass yields did not differ significantly except in entries 9 and 8. Entry 8 which grew undisturbed produced twice as much biomass (16.14 Mg DM $ha^{-1}$) as the ratooned equivalent entry 9 (8.16 Mg DM $ha^{-1}$) and showed a significant difference.

In conclusion, a statistical effect was found in the cutting type as terminal cuttings (ratooned and un-ratooned) produced more biomass than various stem-section cuttings. The length of stem-section cuttings, as well as a vertical or horizontal planting method of setts, showed no significant effect on DM yield, and even cane sections tended to produce more biomass with increasing stem length. Interestingly, entry 8, grown uninterrupted and planted with terminal cuttings, produced more biomass during the experimental period than the equivalent entry 9 with a single intercut, proving a ratooning incompatibility with terminal cuttings.

Varying densities and planting methods of setts were tested for effects on DM yields (Table 4.6), yields of ratooned entries 15 and 16 were accumulated.

Previous studies of plant spacing showed a significant increase of DM yield with increased plant densities under supplemental irrigation and heavy fertilization (Miyagi, 1980; Wijitphan, Lorwilai and Arkaseang, 2009b). In contrast to expectations and literature, in the present investigation, initiation density and planting method (horizontal/vertical) of setts did not affect yield significantly. However, biomass tended to increase with more setts (i.e. entries 1 to 4 or entries 14 to 16) which is generally consistent with former reports.

**Table 4.6 Effect of initiation density and planting method of setts on DM yield in the experimental period 2012 to 2013.**

| | Initiation density (setts m$^{-2}$) | Planting method | Mg DM ha$^{-1}$ Period 17/05/2012 - 27/04/2013 |
|---|---|---|---|
| Entry 1 | 6 | (Horizontal 15 cm) | 0.68 a |
| Entry 2 | 9 | (Horizontal 15 cm) | 0.96 a |
| Entry 3 | 12 | (Horizontal 15 cm) | 2.09 a |
| Entry 4 | 10 | (Horizontal 15 cm) | 1.66 a |
| Entry 14 | 9 | (Vertical 15 cm) | 0.96 a |
| Entry 15* | 9 | (Vertical 15 cm) | 0.64 a |
| Entry 16* | 18 | (Vertical 15 cm) | 1.35 a |

Means followed by the same lowercase letter are not significantly different. * = Yield was accumulated.



The relative distribution of planted biomass inputs and harvested outputs is an important parameter for agronomic crop performance as well as economics. Under this aspect, if for planting used biomass (=input) is more than 50% of totally produced biomass (=output), in other words, more biomass is used for initiation than produced, it is defined as failure of cropping. Figure 4.5 displays a decline in the biomass input/output ratio from setts to canes to terminal cuttings as most productive propagules.

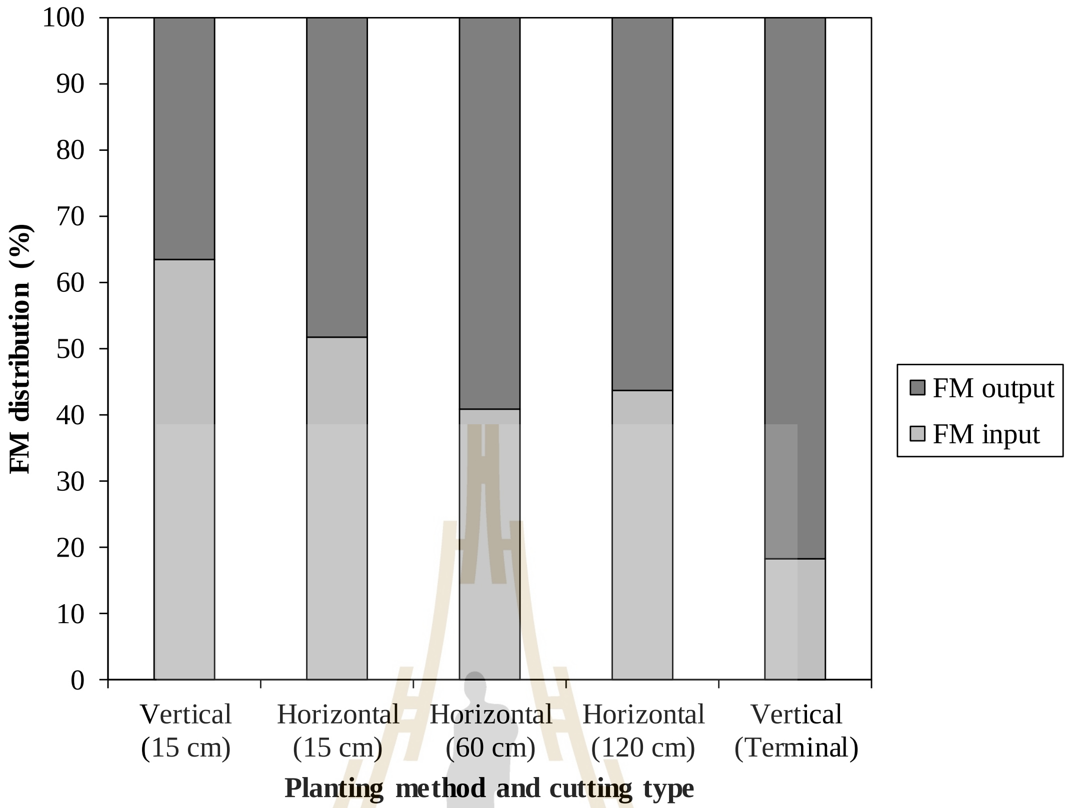



**Figure 4.5** **Relative distributions for fresh mass (FM) input and output sorted by cutting type and planting method in the experimental period 2012 to 2013.**

Setts were unprofitable due to higher inputs than outputs of produced biomass. Even though longer cane sections produced more biomass than required for initiation, the produced biomass counterbalanced biomass used for planting. Terminal cuttings highlighted the ratio as every propagule grew to almost five times its own weight (Figure 4.5).

Locally, cropping starts with the rainy season in May and ends in September, leaving farmland unused during the ensuing dry season. Reports of anticyclical farming strategies starting at the end of the rainy season to produce biomass during the dry season are scarce. The yields of entry 5, cropped from beginning to the end of the rainy season, and the produced biomass of entry 6, cropped from beginning to the end of the dry season, were compared (Table 4.7).

**Table 4.7 Effect of regular and late planting date of setts on dry mass in the experimental period 2012 to 2013.**

| | Mg DM ha$^{-1}$ | |
|---|---|---|
| | Entry 5 | Entry 6 |
| Growing period | 17/05/2012 - 10/09/2012 | 10/09/2012 - 27/04/2013 |
| Yield | 0.19 A | 2.16 A |

Means followed by the same uppercase letter are not significantly different.

Interestingly, entry 6 produced, in 4 months, 2.16 Mg DM ha$^{-1}$ biomass, and thus, much more than entry 5 (0.19 Mg DM ha$^{-1}$) under more favorable conditions, showing September to be a more favorable time for cropping initiation than May. Besides the unexpected derived yield-difference gap, the yield from entry 5 differed insignificantly to entry 6 (Table 4.7).

Previous studies under greenhouse management, showed germination rates of 57.5 to 100% for horizontally planted setts, and 85 to 97.5% for vertically inserted setts (Knoll and Anderson, 2012). A quite constant seedling rate between 8.22 and 13.27% per entry was found except entry 13 (120 cm long cane sections) with 2.48% (Table 4.8). At a second evaluation, the seedling rate increased and dropped drastically with the third evaluation after ratooning. The best seedling rate (21.81%) was found, with entry 6, planted after the rainy season. In a previous experiment, propagation success was affected by N-fertilization and soil moisture directly after planting, while reduced germination of propagules was found under deficient conditions (Rusland, Sollenberger and Jones, 1993; Veenendaal et al., 1996; Woodard and Prine, 1990). Hence, a reduced seedling rate under natural farming (omitted fertilization) was consistent with those literature reports.

**Table 4.8 Evaluation of agronomically important growth parameters of Napier grass under natural conditions in the experimental period 2012 to 2013.**

| | Entry | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 4 | 5 | 6 | 7 | 9 | 11 | 13 | 15 | 16 |
| 1st Evaluation (10/09/12) | | ✂ | | | ✂ | | | | |
| Seedling rate (%) | 11.25 | 11.52 | | 11.74 | | 8.22 | 2.48 | 13.27 | 9.57 |
| Tiller (plant$^{-1}$) | 1.09 | 1.12 | | 1.15 | | 1.64 | 1.65 | 1.32 | 1.09 |
| Height (cm tiller$^{-1}$) | 29.96 | 20.40 | | 24.24 | | 35.43 | 41.44 | 29.60 | 17.00 |
| LAI (%) | 40.81 | 27.39 | | 36.30 | | 34.24 | 45.19 | 50.15 | 59.97 |
| 2nd Evaluation (07/01/13) | | ✂ | | ✂ | ✂ | ✂ | ✂ | ✂ | ✂ |
| Seedling rate (%) | 11.59 | 14.16 | | 10.03 | | 13.21 | 3.33 | 15.12 | 10.80 |
| Tiller (plant$^{-1}$) | 1.98 | 1.22 | | 1.37 | | 1.84 | 4.14 | 2.33 | 1.93 |
| Height (cm tiller$^{-1}$) | 68.63 | 20.43 | | 37.80 | | 38.29 | 58.43 | 33.63 | 22.89 |
| LAI (%) | 58.35 | 46.88 | | 45.14 | | 37.98 | 43.18 | 39.57 | 54.73 |
| 3rd Evaluation (27/04/13) | ✂ | ✂ | ✂ | ✂ | ✂ | ✂ | ✂ | ✂ | ✂ |
| Seedling rate (%) | | 4.79 | 21.81 | 8.03 | 35.80 | 2.02 | 2.69 | 4.94 | 5.86 |
| Tiller (plant$^{-1}$) | | 2.59 | 1.24 | 2.32 | 2.55 | 2.53 | 6.15 | 5.89 | 2.32 |
| Height (cm tiller$^{-1}$) | | 6.04 | 47.85 | 12.63 | 11.17 | 10.36 | 18.00 | 11.52 | 7.22 |
| LAI (%) | | 56.17 | 20.89 | 53.56 | 38.01 | 48.72 | 45.50 | 42.95 | 68.31 |

LAI (Photosynthetic active leaf area index); ✂ (Ratooning).

An effective and plant-considerate harvest method for aerial biomass from Napier grass is ratooning which leaves tussock stubbles and rootstocks for regeneration in the field but eliminates pests and competitive weeds and supports lateral soil occupation in consequence. Large tussock formation via tiller recruitment is found under grazing naturally or ratooning-manipulation mechanically (Pereira et al., 2015). At first evaluation, between 1.09 and 1.65 tillers per plant were counted, finally, increasing steadily to 2.32 and 6.15 tillers per plant. In this experiment, tiller recruitment was much less than reported from previous experiments under conventional farming practice in which an average of 12.3 to 23.7 tillers were counted (Zahid et al., 2002). Ratooning, as an important practice for biomass increase, stimulates tiller recruitment even though it includes the risk of plant losses. However, the risk of plant losses by removing the herbage necessary for regeneration is usually compensated by irrigation and fertilization but drought stress intensifies losses (Woodard and Prine, 1990). As expected, ratooning caused plant losses particularly during the dry season (January harvest). Minimal rainfall in January worsened the natural environmental conditions to unfavorable, shown in Figure 4.1, and led to severe plant losses (Table 4.8).

Moreover, all entries in this experiment recruited tillers steadily and formed tussocks with maturity (Figure 4.6). Tiller recruitment was unaffected by ratooning as their number did not differ between ratooned and un-ratooned plots (entries 4/5). In September, entry 6 showed 1.24 tillers per plant similar to entries planted in May, shown in Table 4.8. In literature, the effects of tussock forming (basal-bud break) or apical dominance (terminal-bud growth) are subjected to phytohormones (Horvath et al., 2003; Tomlinson and O’Connor, 2004). Ratooning ability as an important management

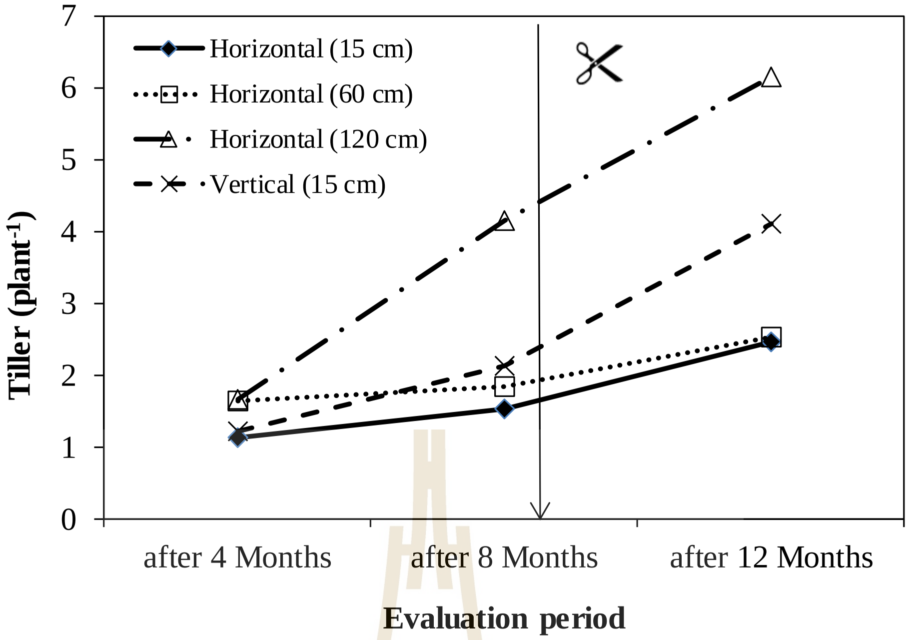



**Figure 4.6** Tiller recruitment of cutting types or planting method in the experimental period 2012 to 2013. ✂ (Ratooning).

practice for biomass increase manually manipulates the phytohormon distribution within plants by breaking the apical dominance mechanically for the stimulation of basal buds. Hence, it was expected that after eliminating terminal buds, tussocks would start to form from the basal-bud break (Gomide et al., 2015). In contrast, ratooning showed no significant effect on tiller recruitment and lateral expansion as basal buds did not break as expected. In a previous investigation of N and P fertilization effects on Napier grass, it was found that under maximum fertilization (120-60 N-P kg $ha^{-1}$ $yr^{-1}$) tiller recruitment (21.5 tillers per plant) increased significantly to zero variant (13.3 tillers per plant) (Zahid et al., 2002). Thus, the natural farming system, due to its reduced fertile conditions, is unfavorable for tiller recruitment and, consequently,

**yields from stalks. After root taking, it was observed that terminal cuttings recruited almost no tillers and grew preferably apically which resulted in high yields from stalks although tussock formation was completely disregarded. Likewise, plant architecture was expected from the exposed node of a vertical inserted sett. In contrast, vertically inserted cane sections preferred to form tussocks (Table 4.8). In contrast to the observation on vertically inserted sett formation, terminal cuttings formed unlikely tussocks after ratooning and DM yield declined as plants perished. With the apically dominant growth of terminal cuttings, basal buds were the matured parts of the plant with lowered regeneration abilities after ratooning (Hartmann et al., 2013). As a result, canes and terminal cuttings differed variously in regeneration, which was attributed to different ratooning tolerances.**

Tillers from setts grew from planting to first evaluation from 17.00 to 41.44 cm, whereas long-stem sections containing entries 11 and 13 developed taller (35.43 and 41.44 cm per tiller). At second evaluation, the tiller's height increased from 22.89 to 68.63 cm per tiller, entry 4 (15 cm setts) thrived vigorously to 68.63 cm per tiller. Tiller height of entry 6, planted in September, was measured 21.81 cm per plant, ranging on the low level of entries planted in May (Table 4.8). Biomass-yields results from herbage production and tiller height are an important agronomic indicator for the evaluation of developing stands. In previous studies, shoot length of setts ranged between 40.9 to 64.8 cm after 14 days under greenhouse conditions and conventionally managed field crops grew an average of 108 to 140 cm per month (Jorgensen et al., 2010; Knoll and Anderson, 2012). Thus, evaluated tiller height in this experiment is irregularly smaller than found in other investigations. Occasionally, reduced tiller height and herbage production was reported in literature as a symptom of drought stress and low fertility (Purbajanti, Anwar and Kusmiyati Widyati, 2012; Zahid et al., 2002). Omitted additional fertilization and irrigation, in compliance with natural farming management, exposed the crops of this experiment to stressing environmental factors and irregular small tillers were the result.

Leaves are the most chlorophyll containing organs of Napier grass and are, thus, a biomass production motor. Hence, the photosynthetic leaf area index (LAI) should be as large as possible and a low LAI is a sign of crop stunting (Kubota et al., 1994; Nagasuga, 2005). The evaluated LAI (Figure 3.2) continuously ranged between 27.39 and 59.97% during the whole experiment. Interestingly, entry 6, planted in September, showed the smallest LAI of 20.89%. Drought stress let leaves dry off and reduced the photosynthetically active leaf area, with dry leaves as an apparent visual sign for the weak condition of the plants (Smit and Singels, 2006). Rainfed crops are extraordinarily exposed to seasonal rainfall changes and thus to fluctuations of drought stress and LAI. Therefore, it was expected that environmental conditions would reduce the LAI and weaken the crops most intensively during the dry season. Interestingly, a contradictory effect was found and LAI was unaffected, as shown in Table 4.8. On the other hand, it was found that planting in September (entry 6) bore the lowest LAI but highest seedling rate. In conclusion, planting in September favored successful seedlings but plantlets were weaker and more drought-stressed than those crops initiated in May.

### 4.4.1 Summary of First Experiment

This study represents the first comprehensive attempt to address a cropping system for Napier grass suitable for high-biomass production under natural conditions. Therefore, farming systems were fundamentally altered in comparison to the conventional, commonly preferred systems. Important system factors such as planting density, cutting type, ratooning intervals and inception time were investigated, matching dry-matter yield as the indicator.

Of all the investigated cropping systems, the least-altered system (planting setts, four-monthly intercutting intervals, incepted in May) produced the smallest biomass under natural conditions. Stem sections of increased length tended to produce more biomass than the setts but not statistically significantly less than those of naturalized Napier grass. A fundamentally altered cropping system (consisting of terminal cuttings, a full year of uninterrupted growth period, single-cut instead of ratooning) resulted in a significantly higher DM yield. However, in this study the highest biomass yield produced (16 Mg DM $ha^{-1}$ $yr^{-1}$) was still smaller than that of conventional cropping systems (40-60 Mg DM $ha^{-1}$ $yr^{-1}$) but higher than naturalized Napier grass (7-11 Mg DM $ha^{-1}$ $yr^{-1}$).



## 4.5 Second Experiment (07/05/2013 until 22/04/2014)

Total precipitation was measured at 1351.70 mm during the replication experiment, shown in Figure 4.1. The accumulated dry biomass of cutting types in correlation to consumed precipitation is shown in Figure 4.7. This figure shows that, with the lowest consumption of rainfall, the smallest biomass was produced. Biomass yields were still close together after a rainfall consumption of approximately 850 mm, only with maximum consumption planted horizontally stem sections (60 and 100 cm long stem sections) and terminal cuttings produced apparently more biomass than setts, depicted in Figure 4.7 as a scissor-like shape. In other words, yields of these three cutting types frame the upper level and yields of setts frame the lower level,

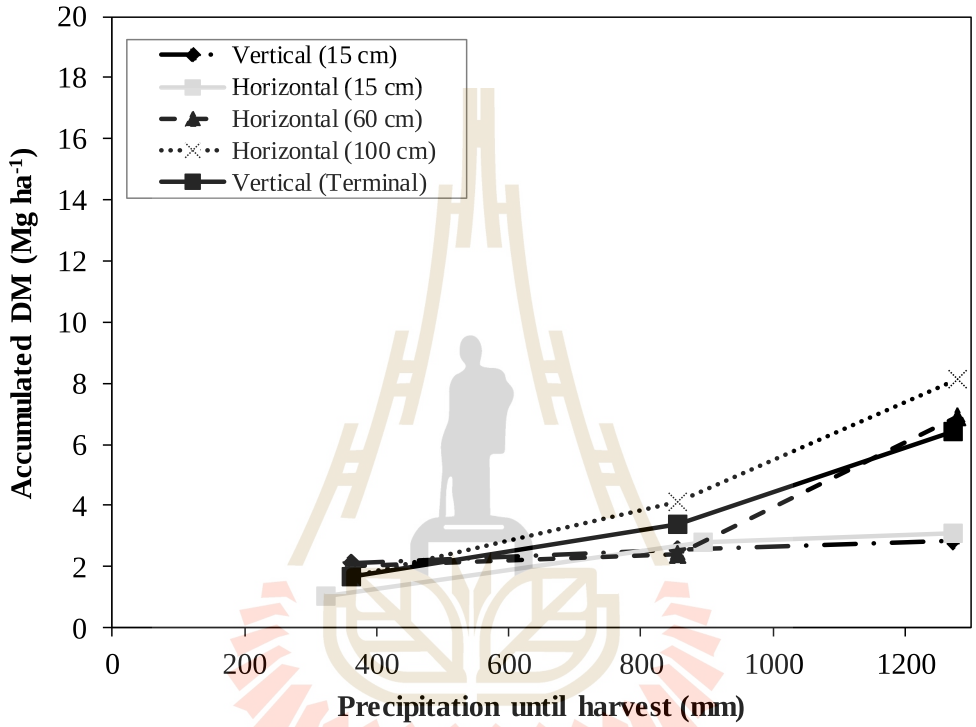



**Figure 4.7** Produced biomass from cutting types in response to quantities of rainfall during second experiment. Yields and precipitation were accumulated for intercutting intervals.

respectively. In conclusion, terminal and long-stem section cuttings used the available rainfall more efficiently for biomass production than setts.

In the first experiment, terminal cuttings had a considerable precipitation-use efficiency and yield per rainfall period, which was also expected for the second experiment. Consistent with expectations, terminal cuttings produced much DM (around 6 Mg DM ha$^{-1}$), but, quite surprisingly, only the third most DM after long-sized stem section cuttings. In the second experiment, terminal cuttings produced less biomass while stem-section cuttings increased yield. Whole stems produced less biomass than terminal cuttings in the first study. It was not expected that the yield would increase to that degree in the replication study. Yield of setts stagnated on a level similar to that in the previous experiment. The yield increase of long-sized stem section cuttings is attributed to healthier plantlets. Chlorophyll-containing organs metabolize sunlight, carbon dioxide and water into biomass by photosynthesis. Hence, under a sufficient water supply, herbage metabolizes more herbage and, consequently, higher biomass yields. Furthermore, yield increases with crop density as more plants accumulate additional biomass for yield. This assumption is in accordance with literature reports in which, under additional irrigation, higher dry-matter yields of sorghum, maize and pearl millet as well as denser stands of Napier grass increased yields as well (Singh and Singh, 1995; Wijitphan, Lorwilai and Arkaseang, 2009b).

Completing the experiment after a full year, the produced biomass finally ranged between 1.40 to 8.16 Mg DM ha$^{-1}$. The bar chart of Figure 4.8 represents the mean dry-matter yield, including the standard deviation for individual spreads. Most standard deviations spread with increasing yield but entry 12 with the highest yield also shows an extraordinarily wide spread, signaling inhomo geneous yields from

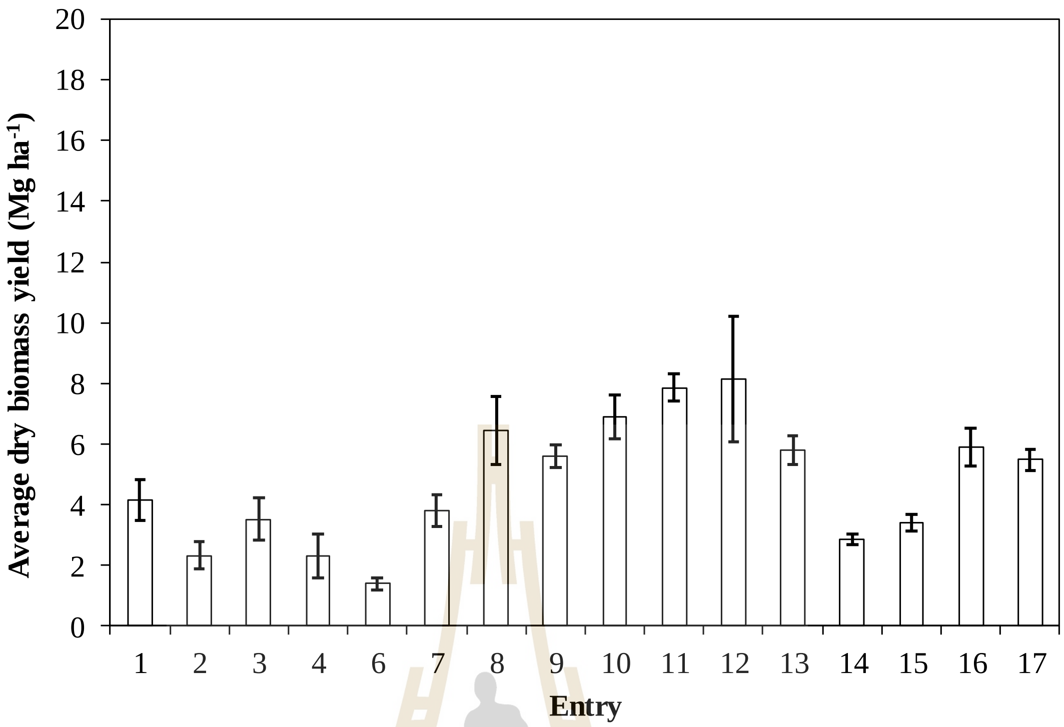



**Figure 4.8** **Distribution of dry-mass yields and specific standard deviation of entries of Napier grass after completion of the study from 2013 to 2014.**

replications. Yields of entries 8 to 13, 16 and 17 ranging between 6 to 8 Mg DM ha$^{-1}$, stood out from entry 12 (100 cm long stem section). Interestingly, entries which were initiated with setts, group on a yield level from 1.40 to 4 Mg DM ha$^{-1}$, were outperformed by entry 16 which yielded roughly 6 Mg DM ha$^{-1}$. Most cumulated DM yields of ratooned entries were higher than from uninterrupted cultivated entries (2/7, 8/9, 10/11, 12/13 and 14/15), showing no negative impacts from ratooning as found under well fertilized management. Interestingly, non-ratooned entry 8 (terminal cuttings) and entry 12 (100 cm long stem section) produced higher yields than ratooned equivalents. In this case, their DM yield was higher than all ratooned sett-containing entries, signaling differences of cutting-type responses towards plant development.

Lounglawan et al. reported on DM yields of King Napier grass, cropped for fodder (also on the campus of SUT) under heavy irrigation and fertilization and under conventional management, at 1.78 Mg DM $ha^{-1}$ with a monthly ratooning regime and 4.68 Mg DM $ha^{-1}$ with a two-monthly ratooning regime (Lounglawan, Lounglawan and Suksombat, 2014). Considering the management, the produced biomass from the present experiment was much lower than reported. However, the yields from this experiment are very consistent with other studies in which fertility was more limited. For example, at Khon Kaen University, under organic production methods, Napier grass cv. 'Taiwan' averaged 1.30 as a zero variant and 1.81, 2.70 and 6.94 Mg DM $ha^{-1}$ under organic manuring (Pholsen et al., 2014).

Twice ratooned after planting, the plants produced the dry biomass of entries 7, 9, 11, 13, 15, 16 and 17 was harvested, measured and statistically analyzed, results are shown in Table 4.9. Regardless of cutting type or planting method, overall yields ranged between 1.97 and 4.13 Mg DM $ha^{-1}$ and did not differ significantly after the first intercutting interval. At the second intercutting interval in April 2014, DM yields also showed insignificant differences. However, yields decreased slightly with intercutting intervals and finally ranged from 1.02 to 3.80 Mg DM $ha^{-1}$. Yields of entry 9 (terminal cuttings) and 13 (100 cm long stem sections) differed significantly from the first to the second harvest while other entries showed insignificant effects between intercutting intervals. Significant yield decrease corroborates the negative effect of ratooning on terminal cuttings, a fact which was found earlier during the first experiment. On the whole, the constant yield decrease of all entries at the end of the wet season was generally consistent with the findings of other experiments (Tudsri et al., 2002).

At completion, entries 2, 8, 10, 12 and 14 were harvested after twelve months of uninterrupted growth and large differences in DM yield from 2.34 to 8.61 Mg DM $ha^{-1}$ were observed, as shown in Table 4.10. The planting method (vertical or horizontal) of entries which were planted with setts showed insignificant effects on produced biomass. Biomass yields of planted long-stem sections (60 or 100 cm) and terminal cuttings also differed insignificantly. Admittedly, significant differences were detected among other cutting types and setts as sett-planted plots produced significantly less biomass than the others. Interestingly, insignificant differences were found between the cumulated DM yields of ratooned and un-ratooned equivalents. The cumulated yields of ratooned entries were mostly even higher than those from un-ratooned equivalents except from terminal cuttings. Even though ratooning is a biomass-increasing practice a clear pattern of increase was not observed in the end. Indeed, intercuts increased yields in just half of all entries in Table 4.10 in the present experiment which is somehow consistent with the previous study of Rengsirikul et al. (Rengsirikul et al., 2011).

**Table 4.9 Effect of cutting type and planting method on DM on two different harvesting dates in the experimental period 2013 to 2014.**

| | | Mg DM ha$^{-1}$ | |
|---|---|---|---|
| | | Intercut | |
| | Cutting type | 26/09/2013 | 22/04/2014 |
| | Av. MC (%) | 73.20 | 62.60 |
| Entry 7 | (Horizontal 15 cm) | 2.78 a, A | 1.02 a, A |
| Entry 9 | (Terminal) | 3.83 a, A | 1.77 a, B |
| Entry 11 | (Horizontal 60 cm) | 4.06 a, A | 3.80 a, A |
| Entry 13 | (Horizontal 100 cm) | 4.13 a, A | 1.66 a, B |
| Entry 15 | (Vertical 15 cm) | 1.97 a, A | 1.44 a, A |
| Entry 16 | (Vertical 15 cm) | 3.13 a, A | 2.79 a, A |
| Entry 17 | (60 cm + terminal) | 3.69 a, A | 1.79 a, A |

Means followed by the same lowercase letter within a column and the same uppercase letter within a row are not significantly different. Av. MC = Average moisture content.

**Table 4.10 Effect of intercuts and cutting type on dry mass in the experimental period 2013 to 2014. Yield of ratooned entries was accumulated.**

| | | Mg DM ha$^{-1}$ | |
|---|---|---|---|
| Cutting type | Comparison | Intercut | Uninterrupted |
| (Horizontal 15 cm) | Entry 7 / Entry 2 | 3.80 a, A | 2.34 b, A |
| (Terminal) | Entry 9 / Entry 8 | 5.60 a, A | 6.44 a, A |
| (Horizontal 60 cm) | Entry 11 / Entry 10 | 7.86 a, A | 6.91 a, A |
| (Horizontal 100 cm) | Entry 13 / Entry 12 | 5.79 a, A | 8.16 a, A |
| (Vertical 15 cm) | Entry 15 / Entry 14 | 3.41 a, A | 2.86 b, A |

Means followed by the same lowercase letter within a column and the same uppercase letter within a row are not significantly different.

The effects of planting method as well as the initial density of setts were expected for biomass production. The produced biomass ranged between 2.34 and 5.92 Mg DM $ha^{-1}$ and was highlighted by entry 16, planted vertically, with 18 setts per square meter, as shown in Table 4.11. Nevertheless, produced biomass yields showed no statistical significance even though higher initiation densities tended to produce more biomass. Each single node possesses root primordia for its germination, suggesting effects on yield as horizontal burying brings more nodes into the ground than vertical insertion. In contrast to the expected higher biomass production from the horizontal planting method, vertically planted setts brought even higher yields than horizontally planted equivalents. This result is consistent with former reports in which vertically inserted setts sprouted more vigorously than horizontal ones buried under greenhouse conditions (Knoll and Anderson, 2012). Statistically insignificant differences in the planting density in this experiment stand in contrast to literature which showed that higher density led to more biomass (Wijitphan, Lorwilai and Arkaseang, 2009b). This contradiction is attributed to fundamentally different crop management than with crops in the experiment of Wijitphan et al. which were managed conventionally but not under natural conditions.

**Table 4.11 Effect of initiation density and planting method of setts on DM yield in the experimental period 2013 to 2014.**

| | Initiation density (setts m⁻²) | Planting method | Mg DM ha$^{-1}$ Period 07/05/2013 - 22/04/2014 |
|---|---|---|---|
| Entry 1 | 6 | (Horizontal 15 cm) | 4.16 a |
| Entry 2 | 9 | (Horizontal 15 cm) | 2.34 a |
| Entry 3 | 12 | (Horizontal 15 cm) | 3.53 a |
| Entry 4 | 10 | (Horizontal 15 cm) | 2.34 a |
| Entry 14 | 9 | (Vertical 15 cm) | 2.86 a |
| Entry 15* | 9 | (Vertical 15 cm) | 3.41 a |
| Entry 16* | 18 | (Vertical 15 cm) | 5.92 a |

Means followed by the same lowercase letter within a column are not significantly different. * DM was accumulated.

The ratio of invested biomass and produced biomass, in short the input:output ratio, is an important key signal of productivity as solely the yield is an imprecise value of agricultural production. For instance, with the increasing length of stem sections, initiation inputs also increased due to heavier weight and thus more biomass yield had to be produced for balance and productivity. Obviously, higher inputs than outputs point to inappropriate propagules, whereas the economic optimum is characterized by small inputs and high outputs. Investigated cutting types required inputs between 15 and 25% and consistently attested the valuable productivity (Figure 4.9). The best ratio was noted from 60 cm long stem sections (15%), the remaining cutting types formed at a 20 and 25% level.

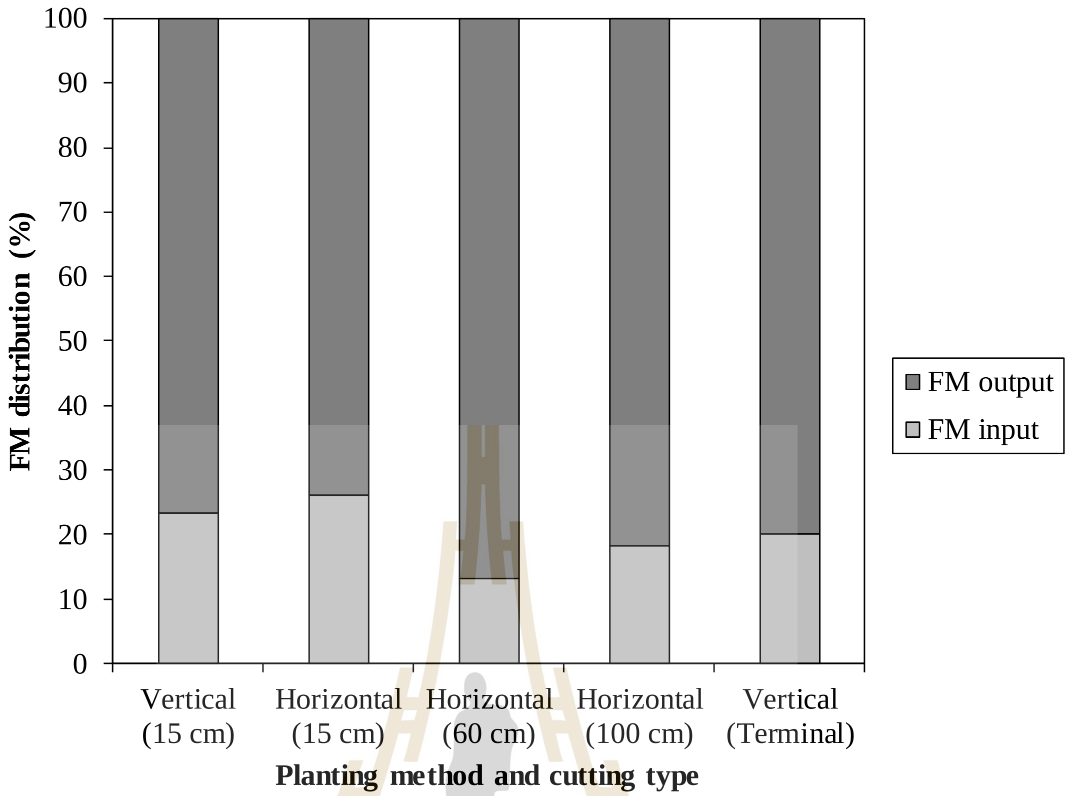



**Figure 4.9** **Relative distributions for fresh-mass (FM) input and output sorted by cutting type and planting method in the experimental period 2013 to 2014.**

Domestically, the cropping period ends with the beginning of the dry season in October when high external irrigation is necessary for cropping success due to missing rainfall. Nevertheless, former experiments with sugarcane have shown opportunities for late-year planting under rainfed conditions (Viator et al., 2005). Reduced yields were expected from late-in-the-year planting and were also found, consistent with literature, shown in Table 4.12. Though late-year planting produced reduced biomass, yields from both regular and late initiation were not significantly different, proving that late planting of Napier grass crops is also possible during the dry season.

**Table 4.12 Effect of regular and late planting date of setts on dry mass in the experimental period 2013 to 2014.**

| | Mg DM $ha^{-1}$ | |
|---|---|---|
| | Entry 7 | Entry 6 |
| Growing period | 07/05/2013 - 26/09/2013 | 05/12/2013 - 22/04/2014 |
| Yield | 2.78 A | 1.40 A |

Means followed by the same uppercase letter within a row are not significantly different.

Optimal germination rates are some of the most important cropping and economic factors characterizing profitable crops with low planting inputs and high-yield outputs. The seedling rate ranged from 13.23 to 23.77% at the first evaluation and declined naturally, including non-ratooned entries, to 5.75 to 11.95% at the second evaluation (Table 4.13). A drastic seedling decline was found at entry 13 (100 cm long stem sections) which decreased from the highest seedling rate (23.77%) at the first evaluation to 9.62% at the second evaluation. As found in the first experiment, the highest seedling rate was found from late-planted entry 6 with 33.91%. However, seedling rates of the present experiment were much lower than in a previous field study in Uganda in which 68 to 96% sprouting cuttings were found on an average, influenced by the cultivar, planted in October, the wettest month during the investigation (Ssekabembe, 1998).

**Table 4.13 Evaluation of agronomically important growth parameters of Napier grass under natural conditions in the experimental period 2013 to 2014.**

| | Entry | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 4 | 6 | 7 | 11 | 13 | 15 | 16 |
| 1st Evaluation (26/09/13) | | | | ✂ | ✂ | ✂ | ✂ | ✂ |
| Seedling rate (%) | 13.23 | 17.65 | | 14.90 | 19.70 | 23.77 | 21.91 | 16.20 |
| Tiller (plant$^{-1}$) | 2.30 | 1.59 | | 1.71 | 1.80 | 2.00 | 2.00 | 1.68 |
| Height (cm tiller$^{-1}$) | 68.26 | 54.37 | | 77.51 | 125.75 | 95.87 | 92.27 | 115.77 |
| LAI (%) | 60.97 | 58.79 | | 48.66 | 54.67 | 40.49 | 72.74 | 67.94 |
| 2nd Evaluation (22/04/14) | ✂ | ✂ | ✂ | ✂ | ✂ | ✂ | ✂ | ✂ |
| Seedling rate (%) | 9.58 | 5.75 | 33.91 | 7.60 | 11.95 | 9.62 | 11.73 | 7.87 |
| Tiller (plant$^{-1}$) | 2.79 | 2.38 | 2.18 | 1.93 | 3.05 | 2.44 | 4.35 | 2.94 |
| Height (cm tiller$^{-1}$) | 184.41 | 160.41 | 18.79 | 44.47 | 93.29 | 65.34 | 70.23 | 91.36 |
| LAI (%) | 1.29 | 11.83 | 59.20 | 21.28 | 12.72 | 11.35 | 26.04 | 14.03 |

LAI (Photosynthetic active leaf area index); ✂ (ratoon).

As it matures, the tiller of Napier grass forms large tussocks which also suppress competitive weeds through lateral soil occupation. Additionally, tillers form vigorous stems which increase DM yield more effectively than herbal biomass (Ferraris and Sinclair, 1980). On an average, between 1.59 and 2.30 tillers per plant were recruited during the first trial and increased to 1.93-4.35 tillers per plant at the second evaluation. In a previous study, also conducted in the Nakhon Ratchasima Province, various cultivars recruited between 21.7 to 43.3 tillers m$^{-2}$ (equivalents 8.68 to 17.32 tillers per plant for the present experiment) after twelve months under very fertile conditions, increasing with each intercutting interval (Rengsirikul et al., 2011). In contrast to other reports, plantlets, with and without intercutting intervals, increased tillers with maturity. In the present investigation they could not be stimulated by intercutting intervals (Clavero, 1997). However, tiller recruitment was found to accelerate with fertility, namely, N fertilization tended to increase tiller numbers and biomass yield. The effect is more pronounced with frequent intercutting intervals (Ferraris, 1980).

Besides the tiller number, height is one other important parameter for dry-matter yield attained from lignified stems. In the current investigation, tillers emerged from the first planting to the first evaluation between 54.37 and 125.75 cm, stood out by entry 11 (60 cm stem section) and entry 16 (18 vertical inserted setts). At the second evaluation, ratooned entries emerged between 44.47 and 93.29 cm, with entries grown uninterrupted increasing in height to 160.41 and 184.41 cm and late-planted entry 6 increased to 18.79 cm. Overall, plant height in this study was much lower than that of reports on well fertilized and irrigated plots where the cultivar 'Bana' reached a height of 528.7 cm when cut after twelve months, in contrast to 'Muaklek' which reached 259.0 cm (Rengsirikul et al., 2011). However, the heights of entries are very consistent with studies in which a fertilizer supply of N and P was studied and with the zero-control, emerged with 142.7 and 147.0 cm in the subsequent year (Zahid et al., 2002).

During first evaluation, LAI ranged from 40.49 to 72.74% and showed a drastic decline at evaluation after the dry season down to a range of 1.29 and 26.04%. Thus, crops were healthier during the rainy season and became weaker during the dry season (there was almost no rainfall from October to April, Figure 4.1). The LAI of late-planted entry 6 was observed at 59.20%. Due to an overall decline of LAI during the dry season it was previously reported that drought stress caused leaf dry-off (Smit and Singels, 2006). Even though the unexpectedly low LAI is attributed to the very severe dry season during the experiment, it is inconsistent with other observations of an average of 84.2 to 89.4% of live leaves on rainfed Napier grass crops (Rengsirikul et al., 2011).

### 4.5.1 Summary of Second Experiment

The second experiment replicated the rationale of first experiment and therefore investigated an altered farming method suitable for natural conditions. Planting density, cutting type, ratooning intervals and inception time were examined for their effects on dry-matter yield.

In summary, the minimally altered farming system (planting setts, most-frequent intercutting intervals, begun in May) produced the lowest biomass under natural conditions. It was possible to produce significantly more biomass, between 6 and 8 Mg DM ha$^{-1}$, by using alternative plant parts as propagules (whole stem sections or terminal cuttings). The most altered farming system (using whole stem sections or terminal cuttings, with a full year of uninterrupted growth period, single-cut instead of ratooning) resulted in significantly higher DM yields. However, the produced biomass was still lower than reported yields of conventionally managed crops even though a promising input:output ratio between 15-25:85-75% was observed. Nevertheless, the produced biomass was consistent with reports from unfertilized plots or the estimated yield of naturalized Napier grass.

## 4.6 Third Experiment (07/05/2013 until 22/04/2014)

A third experiment was conducted, parallel to the second experiment, examining the effects of reduced propagule inputs on biomass yield. For this third experiment, the Napier grass cultivar 'Pakchong' was chosen due to its similar yield potential with most tall growing cultivars that are commonly found in Thailand (Mani-in et al., 2014). After the completion of the experiment, DM yields ranged from 4 to 10 Mg DM $ha^{-1}$ illustrated as bar charts in Figure 4.10. Similar standard deviations spread moderately and show the yield variances between entries, DM yield homogeneity is also confirmed by the main yield pattern between 6 and 8 Mg DM $ha^{-1}$. Entry 26 and 27 (with setts inserted at an angle of 45°) were observed to produce the least biomass (4 to 5 Mg DM $ha^{-1}$) in contrast to entry 25 (100 cm long stem sections) which stood out with 10 Mg DM $ha^{-1}$. It is worth noting that yields from terminal cuttings were high and almost the same level as entry 25. The produced biomass yields observed with most entries are very consistent with reports of previous experiments, where Napier grass cv. 'Pakchong' exceeded 6.4 Mg DM $ha^{-1}$ $yr^{-1}$ under moderate organic fertilization in Bhutan (Wangchuk et al., 2015). Interestingly, the highest and lowest yields (entries 21 and 25 as well as 26 and 27), in the present experiment, ranged on same level as in the experiment conducted in Bhutan.

At the first intercutting interval, the produced biomass ranged from 2.71 to 7.23 Mg DM $ha^{-1}$ (entries 27 and 25), shown in Table 4.14. The lowest DM yields were measured from entries 26 and 27 which contained inserted setts at an angle and one node exposed in contrast to the highest yield that was observed from entry 25 (100 cm long stem section) which contained the most nodes in the ground. As a result, entry 25 differed significantly from entry 27 but also from entry 22 (60 cm long stem section).

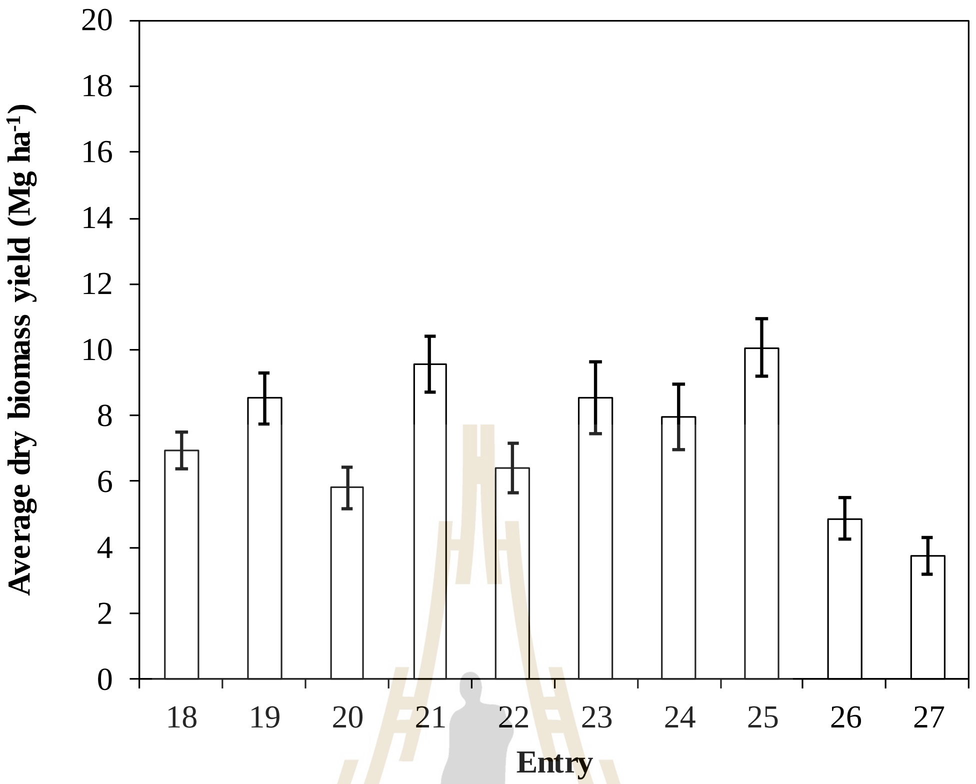



**Figure 4.10** **Distribution of dry-mass yields and specific standard deviation of entries of Napier grass cv. 'Pakchong' after completion of the study from 2013 to 2014.**

At the second harvest, all DM yields declined drastically and finally reached a level between 1.04 and 3.63 Mg DM ha$^{-1}$ at which no significant differences were found between entries. Entry 18 (setts), 22 (60 cm long stem section), 24 (60 cm stem section + terminal) and 25 (100 cm long stem section) produced significantly less biomass between intercutting periods. In conclusion, ratooning clearly tended, although not in an obviously significant way, to reduce biomass and, thus, had a negative effect during the dry season. Terminal cuttings (entry 21, 5.94 and 3.63 Mg DM ha$^{-1}$) showed a massive ratooning incompatibility including a massive yield decrease. The decrease in the third experiment was unexpectedly smaller than that which was expected in the two previous experiments. The cumulated dry biomass of entry 25 differed significantly from entries 18, 22, 26 and 27 which is attributed to the thriving development of this specific cutting type.

**Table 4.14 Effect of planting method and cutting type on dry biomass of Napier grass cv. ˈPakchongˈ on two harvesting dates in the experimental period 2013 to 2014.**

| | | Mg DM ha$^{-1}$ | | |
|---|---|---|---|---|
| | | Intercut | | |
| | Cutting type and planting method | 23/11/2013 | 21/04/2014 | Total |
| | Av. MC (%) | 71.70 | 62.60 | |
| Entry 18 | (Horizontal 15 cm) | 5.15 ab, A | 1.79 a, B | 6.94 b, A |
| Entry 19 | (Horizontal 15 cm) | 6.80 ab, A | 1.74 a, A | 8.54 ab, A |
| Entry 20 | (Horizontal 15 cm) | 4.17 ab, A | 1.64 a, A | 5.81 ab, A |
| Entry 21 | (Vertical Terminal) | 5.94 ab, A | 3.63 a, A | 9.56 ab, A |
| Entry 22 | (Horizontal 60 cm) | 5.23 b, B | 1.19 a, C | 6.42 b, A |
| Entry 23 | (Vertical 15 cm) | 6.01 ab, A | 2.54 a, A | 8.55 ab, A |
| Entry 24 | (Horizontal 60 cm + Terminal) | 6.56 ab, A | 1.39 a, B | 7.96 ab, A |
| Entry 25 | (Horizontal 100 cm) | 7.23 a, B | 2.83 a, C | 10.07 a, A |
| Entry 26 | (45° 15 cm) | 3.34 ab, A | 1.54 a, A | 4.88 b, A |
| Entry 27 | (45° 15 cm) | 2.71 b, A | 1.04 a, A | 3.76 b, A |

Means followed by the same lowercase letter within a column and the same uppercase letter within a row are not significantly different. Av. MC = Average Moisture content.

In contrast to preceding experiments, terminal cuttings (entry 21) did not produce the most biomass until the first intercut. 40% of its total biomass was produced after ratooning, and thus, terminal cuttings were less incompatible towards ratooning than in previous experiments (Figure 4.11). During the dry season, the least DM was produced from entry 22 (60 cm stem section) and entry 24 (60 cm stem section + terminal) which were able to bear 20% of the total biomass.

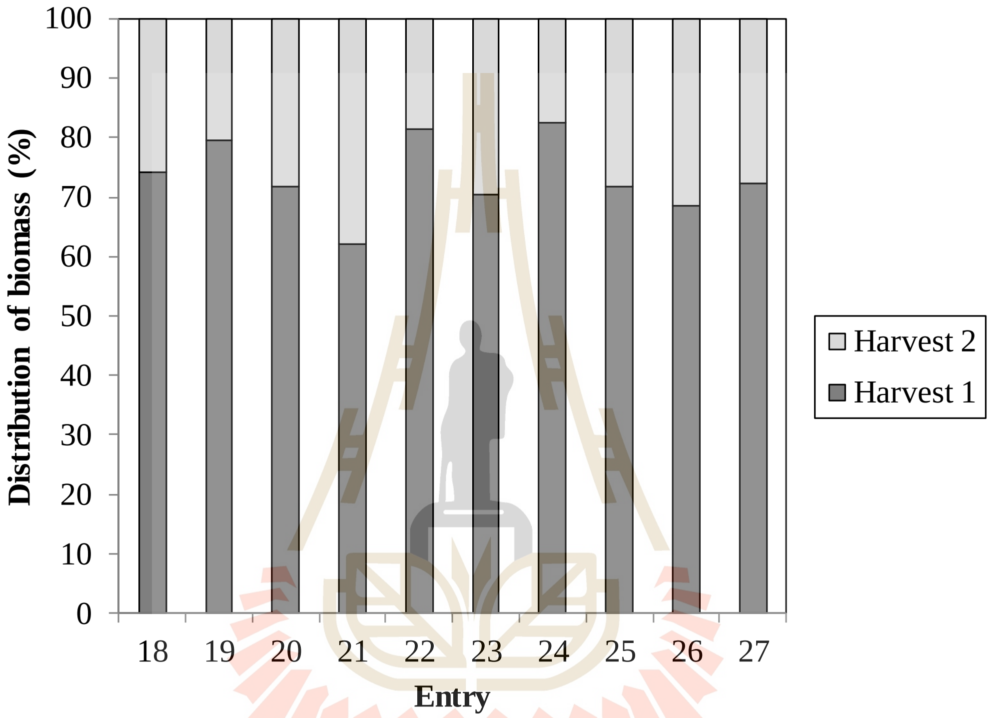



**Figure 4.11** **Relative distributions of entry-specific produced biomass sampled at two intercut intervals in the experimental period 2013 to 2014.**

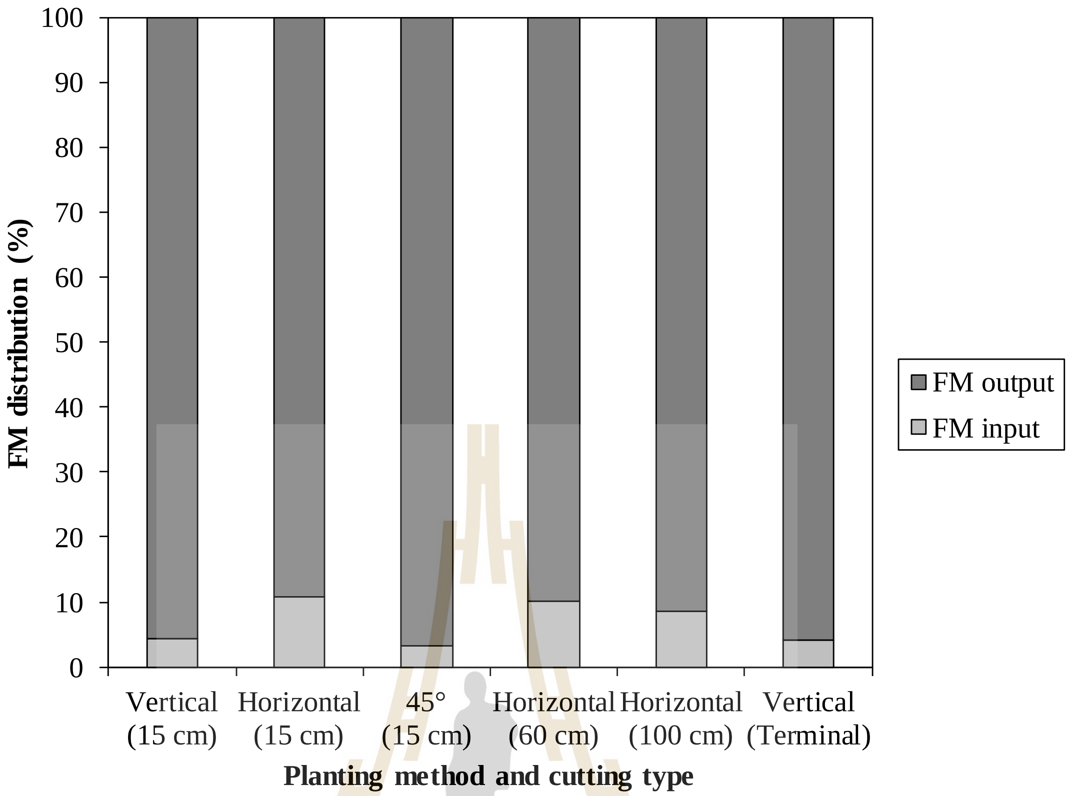



**Figure 4.12 Relative distributions for planting-invested biomass input and yield output sorted by planting method and cutting type of Napier grass cv. 'Pakchong' in the experimental period 2013 to 2014.**

All entries thrived well and were able to multiply biomass almost ten times more from initiation until harvest, which is clearly the highest productivity of all experiments (Figure 4.12). Although not obvious from DM yields, most biomass was produced from terminal cuttings and vertically inserted setts, with and without angle, and had a high productive input:output ratio of almost 5:95%. Thus, vertical insertion of setts was found to be a more favorable planting method and more productive than horizontal burying, which is consistent with literature reports (Knoll and Anderson, 2012). However, the most unfavorable relation between input and output was detected for horizontally buried setts and stem-section cuttings. Compared with the findings of the two other studies, at present, the overall investigated and produced biomass relation is the most productive.

### 4.6.1 Summary of Third Experiment

In the third experiment, Napier grass crops of cv. 'Pakchong' were established under natural conditions for examining the effects of reduced propagules on biomass production. The conventional farming system was altered to various degrees and investigated for two intercutting intervals. The least-altered cropping system (inserting setts with an angle of 45°) yielded the lowest amount in absolute Mg DM $ha^{-1}$ but showed the highest relative productivity (input:output ratio). In contrast, a fundamentally altered farming system containing 100 cm stem sections, followed by terminal cuttings, produced the most cumulated absolute DM. Although the absolute biomass of these cutting types was highest, only terminal cuttings had a favorable relative DM distribution (input:output ratio). However, cumulatively produced biomass in the present experiment ranged between 7 and 10 Mg DM $ha^{-1}$ which is slightly higher than literature reports of 'Pakchong' cultivars under moderate organic fertilization. In conclusion, results were only clear for the terminal cuttings which produced the most absolute and relative biomass yield in the tested natural farming system.

## 4.7 Comprehensive Experiment (2012 until 2014)

In every separate experiment biomass was produced successfully under natural conditions by all entries and plots. Entry-specific produced biomass within experiments was content-addressed to accumulated precipitation until intercut, shown in Figure 4.13. The equality of the experiments is signaled by very similar function slopes of gradients. Homogeneity of variances between cultivars, and, thus, for experiments tested with the cultivar at SUT campus, was proven by insignificant DM yield differences of control entry 7 (9 setts $m^{-2}$, two intercut intervals) of each individual experiment (Table 4.15). Furthermore, the homogeneity of variances was proven by insignificant DM yield differences between entries 7 and 19, consisting of equal parameters but differing in cultivar, as the cultivar at the SUT campus and cv. 'Pakchong' were tested in the years 2013-2014. In summary, comparability between individual experiments is given (Table 4.18).

Taken together, DM yields ranged between 0.5 and 10 Mg DM $ha^{-1}$, except for 16 Mg DM $ha^{-1}$ in the first experiment, with moderate spreads within groups of same intercutting interval. With increasing consumption of rainfall, more biomass was produced and yield-level of entries increased simultaneously. In the experiment from 2012-2013, spreads were apparently the widest with a 16 Mg DM $ha^{-1}$, a outperforming spike from entry 8 within the group that consumed 800 mm rainfall until harvest. However, entries of the first experiment showed the widest range of produced biomass in comparison to the other experiments. In previous long-term studies under rainfed conditions, drastic yield decrease from 36.3 to 5.0 Mg DM $ha^{-1}$ in four successive years have been reported (Knoll et al., 2011). In contrast to this report, the yields of the present experiments increased successively. However, this observation is attributed to higher rainfall in subsequent years and the complete field clearance and new initiation of plots after the completion of each experiment in contrast to the long-term study of Knoll et al. who measured yields of the same crop which matured with years.

In line with local cropping practices, the present study was initiated at the beginning of the rainy season with an intercutting interval at the end of the rainy season

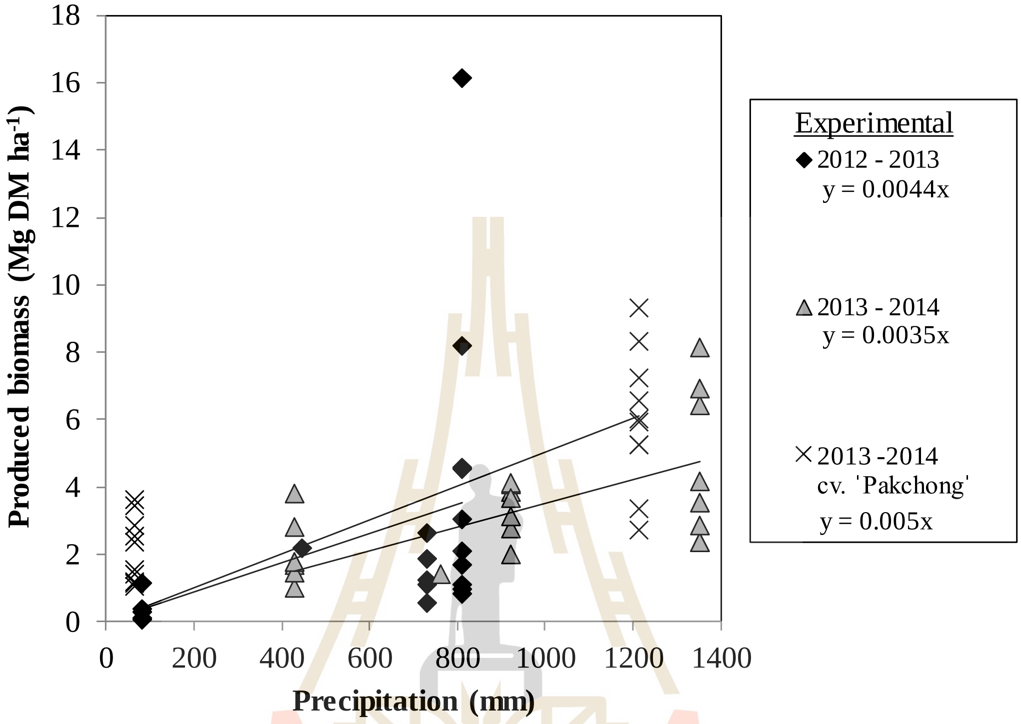



**Figure 4.13 Experiment-specific produced biomass from entries in response to quantities of rainfall during experiments from 2012 to 2014. Precipitation was accumulated for the intercutting intervals.**



and a complete cut after a full year. Irrespective of tested treatments, more biomass was produced during the rainy seasons than in the dry seasons, shown in Table 4.15. Stem sections are the most common raw material for propagules for propagation of tall grasses such as Napier grass and regeneration from a stem section into a plant starts from the section's primordia including attached buds (Bakker, 1999). Thus, stem sections with increasing length also contain more buds and should produce more plantlets and biomass from more buds in the ground. In contrast to this expectation, DM yields of setts, regardless of horizontal or vertical planting method or increasing length of stem sections which directly affected the number of buds in the ground, produced insignificant quantities of biomass during the full experimental period from 2012 to 2014. Nevertheless, entries planted with increased stem-section length also tended to produce increased yields. In contrast to other propagules, yields of 60 cm long stem sections (entry 11) differed significantly between years and all DM yields in the replication experiment in 2013-2014 were significantly higher than in the previous experiment. The cumulatively produced biomass of stem sections (entry 13, 120/100 cm long-sized stem sections) differed insignificantly between years even when 20 cm shorter stem sections were used in the replication (Table 4.15).

After the completion of the experiments, between 0.96 and 16.14 Mg DM $ha^{-1}$ were produced in the years 2012 and 2013 and between 2.34 and 8.16 Mg DM $ha^{-1}$ in the years 2013 and 2014 by uninterrupted growing entries (Table 4.16). Thus, the produced biomass had a smaller spread due to more homogeneous yields in the second experimental year. The effects of cutting type on biomass production were detected since most biomass was produced statistically significantly from terminal cuttings (entry 8, 16.14 Mg DM $ha^{-1}$) while insignificant differences of DM yield were found between various long-stem sections or the sett planting method in the cropping period from 2012 until 2013. Indeed, the least biomass was produced from setts, regardless of planting method (vertical or horizontal), with 0.96 Mg DM $ha^{-1}$, but stem-section cuttings tended to produce more biomass with increasing stem-section length (entries 10 and 12), as shown in Table 4.16. Entries 10, 12 and terminal cuttings repeatedly produced significantly more biomass than sett-containing entries during the experimental years 2013-2014. In conclusion, the cutting type proved to have an effect

**Table 4.15 Effect of planting method and cutting type on dry biomass of Napier grass at two intercutting intervals during the years 2013 to 2014.**

| | | Mg DM ha$^{-1}$ | | | | | |
|---|---|---|---|---|---|---|---|
| | | Experimental and harvesting season | | | | | |
| Entry | Planting method and cutting type | 2012-2013 | | | 2013-2014 | | |
| | | Rainy | Dry | Total | Rainy | Dry | Total |
| 7 | (Horizontal 15 cm) | 1.01 a, A | 0.31 a, A | 1.32 a, A | 2.78 a, A | 1.02 a, A | 3.80 a, A |
| 11 | (Horizontal 60 cm) | 1.22 a, B | 0.04 a, B | 1.26 a, B | 4.06 a, A | 3.80 a, A | 7.86 a, A |
| 13 | (Horizontal 120/100 cm) | 2.60 a, AB | 1.14 a, B | 3.74 a, AB | 4.13 a, AB | 1.66 a, AB | 5.79 a, A |
| 15 | (Vertical 15 cm) | 0.54 a, AB | 0.10 a, B | 0.64 a, AB | 1.97 a, A | 1.44 a, AB | 3.41 a, AB |
| 16 | (Vertical 15 cm) | 1.09 a, A | 0.26 a, A | 1.35 a, A | 3.13 a, A | 2.79 a, A | 5.92 a, A |

Means followed by the same lowercase letter within a column and the same uppercase letter within a row are not significantly different.

on produced biomass as setts produced the least biomass in the experiments conducted from 2012-2014 and, thus, showed the lowest suitability for the natural farming system, even though vertically inserted setts produced significantly more biomass in the replication than in the first experiment.

The one-cutting type containing plots of terminal cuttings (entry 9) produced most dry biomass as a mix of stem sections of 60 cm length and terminal cuttings (entry 17) that produced more biomass than entry 11 that contained unmixed stem sections of 60 cm length in the years 2012-2013 (Table 4.17). On that occasion, entry

9 yielded significantly more than the both other entries. A reversed trend was found in the years 2013-2014 when entry 11 produced the most biomass. To this end, DM yields of entries 9 and 11, but not entry 17, differed significantly between years. This ambiguity is attributed to the risk of the volatile development of a single-cutting type when terminal cuttings developed favorably in the first experiment and 60 cm long stem sections in the second experiment. Consequently, the combination of cutting types for biomass production showed a positive interaction effect and led to a more homogeneous stand formation that resulted in steady yield, proved by the insignificant year effects of entry 17. Volatile plant-propagule development is attributed to certain propagule-reproduction dynamics such as terminal cuttings which expand vertically and stem sections horizontally. By mixing patterns of the reproduction dynamics, stand development is optimized by covering the soil's surface and stands form more quickly than from a single-cutting type. Additionally, combining cutting types

**Table 4.16 Effect of cutting type and sett planting method on dry mass of Napier grass in the experimental periods during the years 2012 to 2014.**

| | | Mg DM $ha^{-1}$ | |
|---|---|---|---|
| | | Experiment | |
| | Planting method and cutting type | 2012–2013 | 2013–2014 |
| Entry 2 | (Horizontal 15 cm) | 0.96 b, A | 2.34 b, A |
| Entry 8 | (Terminal) | 16.14 a, A | 6.44 a, B |
| Entry 10 | (Horizontal 60 cm) | 3.05 b, A | 6.91 a, A |
| Entry 12 | (Horizontal 120/100 cm) | 4.51 b, A | 8.16 a, A |
| Entry 14 | (Vertical 15 cm) | 0.96 b, B | 2.86 b, A |

Means followed by the same lowercase letter within a column and the same uppercase letter within a row are not significantly different.

**Table 4.17 Effect of one-cutting type and combined cutting types on dry mass of Napier grass in the experimental periods during the years 2012 to 2014.**

| | | Mg DM ha$^{-1}$ | |
|---|---|---|---|
| | | Experiment | |
| | Cutting type | 2012–2013 | 2013–2014 |
| Entry 9 | (Terminal) | 8.16 a, A | 5.60 a, B |
| Entry 11 | (Horizontal 60 cm) | 1.26 b, B | 7.86 a, A |
| Entry 17 | (Horizontal 60 cm + Terminal) | 4.58 b, A | 5.48 a, A |

Means followed by the same lowercase letter within a column and the same uppercase letter within a row are not significantly different.

buffered yield spreads by reducing rooting incompatibility of a certain cutting type, for instance, from individual environmental sensitivity.

Higher yields, but not statistically significantly higher, were observed from entries of the experiment with Napier grass cv. 'Pakchong' which were generally initiated with fewer propagules than the other two experiments. 'Pakchong' produced between 6.42 and 10.07 Mg DM ha$^{-1}$ and, thus, continuously more biomass-except for entry 15 (100 cm long stem sections) - than from equivalents in 2013-2014, shown in Table 4.18. Apparently, more biomass was produced from the cultivar 'Pakchong' during the rainy season than during the dry season. This result is consistent with the previously tested cultivar where biomass production was also affected by ratooning during the dry season. For instance, significantly more dry biomass was produced during the rainy season from entries 22 (60 cm stem section), 25 (100 cm stem section) and 24 (terminal+60 cm stem section) than during the dry season. In contrast to previous findings, stem sections of 60 cm and 100 cm length (entries 22 and 25) framed the minimum and maximum amount of totally produced DM and thus differed significantly between years. A previous study proved that intercutting intervals during the dry season resulted in yield decline and present findings are very consistent with it (Tudsri et al., 2002). On the other hand, all entries initiated with 60 or 100 cm stem sections produced unsteady DM yields and, thus, statistical significances between years. Hence, combining terminal cuttings with stem-section cuttings, entries 17 and 24, for instance, stabilized biomass production.

Interestingly, DM yields of 'Pakchong' setts, irrespective of planting method, were insignificantly different from the Napier grass cultivar from the SUT campus even though more biomass was produced by entries 19 and 23 than from entries 7 and 15. Particularly, entry 23 (4 vertically inserted setts) produced a total of 8.55 Mg DM ha$^{-1}$ with half the initiation input of entry 15 (9 vertically inserted setts) which produced 3.41 Mg DM ha$^{-1}$. A similar result was observed for terminal cuttings (entry 21, 4 cuttings m$^{-2}$) which bore the second highest total DM yield (9.56 Mg DM ha$^{-1}$) under reduced initiation inputs, proving to produce higher yields than found in the earlier experiments (Table 4.18).

The data indicate that individual plantlets of Napier grass cv. 'Pakchong' had a more favorable establishment performance (i.e. rooting rate, viable sprouts or stand dynamic) than SUT-campus Napier grass equivalents. During the field experiment, it was observed that 'Pakchong' took roots quickly and had favorable stand architecture by stocking vertically and horizontally, which was favorable for sunlight consumption and herbage growth. Various cultivar responses towards establishment, for example cv. 'Mott', which is more difficult to establish than tall Napier grass, are described in literature (Rusland, Sollenberger and Jones, 1993). The authors of that study demonstrated, that in addition to increasing N fertilization and soil moisture, the cultivar is critical to subsequent establishment performance. Hence, the higher DM yields of 'Pakchong' are attributed to the easier establishment than the parallel experiment with the tall Napier grass from SUT campus which was tested under same field conditions.

**Table 4.18 Effect of cutting type, initiation density and harvesting season on DM yield of two different Napier grass cultivars.**

| | | Mg DM ha$^{-1}$ | | | | | |
|---|---|---|---|---|---|---|---|
| | | Experimental and harvesting season | | | | | |
| Entry (Density m$^{-2}$) | Planting method and cutting type | 2013-2014 | | | 2013–2014 cv. 'Pakchong' | | |
| | | Rainy | Dry | Total | Rainy | Dry | Total |
| 7, 19 (9, 9) | Horizontal 15 cm | 2.78 a, AB | 1.02 a, B | 3.80 a, AB | 6.80 ab, A | 1.74 a, AB | 8.54 ab, A |
| 9, 21 (9, 4) | Terminal | 3.83 a, A | 1.77 a, B | 5.60 a, A | 5.94 ab, AB | 3.63 a, AB | 9.56 ab, AB |
| 11, 22 (3, 3) | Horizontal 60 cm | 4.06 a, AB | 3.80 a, ABC | 7.86 a, AB | 5.23 b, B | 1.19 a, C | 6.42 b, A |
| 13, 25 (3, 2) | Horizontal 100cm | 4.13 a, C | 1.66 a, D | 5.79 a, BC | 7.23 a, B | 2.83 a, CD | 10.07 a, A |
| 15, 23 (9, 4) | Vertical 15 cm | 1.97 a, A | 1.44 a, A | 3.41 a, A | 6.01 ab, A | 2.54 a, A | 8.55 ab, A |
| 17, 24 (3+3, 2+2) | Terminal+ Horizontal 60 cm | 3.69 a, AB | 1.79 a, B | 5.48 a, A | 6.56 ab, A | 1.39 a, B | 7.96 ab, A |

Means followed by the same lowercase letter within a column and the same uppercase letter within a row are not significantly different.

In the experiments from 2012 to 2014, setts produced between 0.64 and 8.54 Mg DM ha$^{-1}$ (Table 4.19). Insignificant DM yield in response to the densities or planting method of setts was obtained within particular experiments. In the first experiment from 2012 to 2013, the smallest quantity of dry biomass was measured for densities of six and nine setts per square meter (entries 1 and 2) which differed significantly from successive years. However, a density of twelve setts per square meter (entries 3 and 20) had the lowest yield in the first experiment but differed insignificantly from the results of further experimental years. Nevertheless, very ambiguous results were found in the years 2013-2014 when sparser stands produced more biomass than denser stands, i.e. entries 1 and 18 (6 setts $m^{-2}$) produced more biomass than entries 3 and 20 (12 setts $m^{-2}$). These results contradict the reports of earlier experiments in which it was demonstrated that DM yields increased with planting density under high fertility (Wijitphan, Lorwilai and Arkaseang, 2009b). The planting method of setts had insignificant effects on biomass production during the full experiment. These results are very consistent with earlier findings which demonstrated insignificant effects of the planting method on shoot mass (Knoll and Anderson, 2012). No clear trend or recommendation for planting method or planting density resulted from the experiments. In conclusion, clear decisions for a planting method for setts can only be made under further aspects of field handling and economics.

Since agriculture in Thailand is heavily dependent on rainfall, in the dry seasons fields lie fallow. As expected, the season had significant effects on biomass production in the years 2013-2014 (Figure 4.14). This effect is very consistent with the study on effects of the cutting height of various Napier grass cultivars conducted at the Suwanvajokkasikit Research Station, where it was observed that the intercut at the end of the wet season of Napier grass reduced yields massively (Tudsri et al., 2002). On the contrary, no effect of the season on DM yield was observed in the experiment during the years 2012 to 2013. DM produced from the replication experiment in 2013-

2014 was significantly smaller during the rainy season than in the previous year or with the cv. 'Pakchong'. However, insignificant effects on biomass production were observed for the dry season or for the uninterrupted cropping period (rainy+dry season).

**Table 4.19 Effect of initiation density and planting method of setts on DM yield of two different Napier grass cultivars.**

| | | | Mg DM ha$^{-1}$ | | |
|---|---|---|---|---|---|
| | Explanatory factor | | | Experiment | |
| Entry | Planting method | Density (setts m$^{-2}$) | 2012–2013 | 2013–2014 | 2013–2014 cv. 'Pakchong' |
| 1, 18* | (Horizontal 15 cm) | 6 | 0.68 a, B | 4.16 a, A | 6.94 a, A |
| 2, 19* | (Horizontal 15 cm) | 9 | 0.96 a, B | 2.34 a, AB | 8.54 a, A |
| 3, 20* | (Horizontal 15 cm) | 12 | 2.09 a, A | 3.53 a, A | 5.81 a, A |
| 4 | (Horizontal 15 cm) | 10 | 1.66 a, A | 2.34 a, A | - |
| 15* | (Vertical 15 cm ) | 9 | 0.64 a, A | 3.41 a, A | - |
| 16* | (Vertical 15 cm ) | 18 | 1.35 a, A | 5.92 a, A | - |

Means followed by the same lowercase letter within a column and the same uppercase letter within a row are not significantly different. * = DM was accumulated.

The late planting date of setts (entry 6), shortly before the dry season started, had no significant effect on DM yield (Tables 4.7, 4.12 and 4.20). The agronomic performance of the late-planted entry 6 was considerably homogenous as parameters of seedling rate, the number of tillers or the plant height did not differ significantly within experimental years (Table 4.21). In conclusion, Napier grass crops for biomass production also flourished with a promising potential during the dry season which enabled year-round cropping. The successful cropping of Napier grass during the dry season agrees with the work of Tekletsadik et al. in which pre-rooted plantlets of dwarf Napier grass on well-fertilized plots produced almost the same DM yield in the dry (20.84 t/ha) as in the wet (30.73 t/ha) season (Tekletsadik et al., 2004).

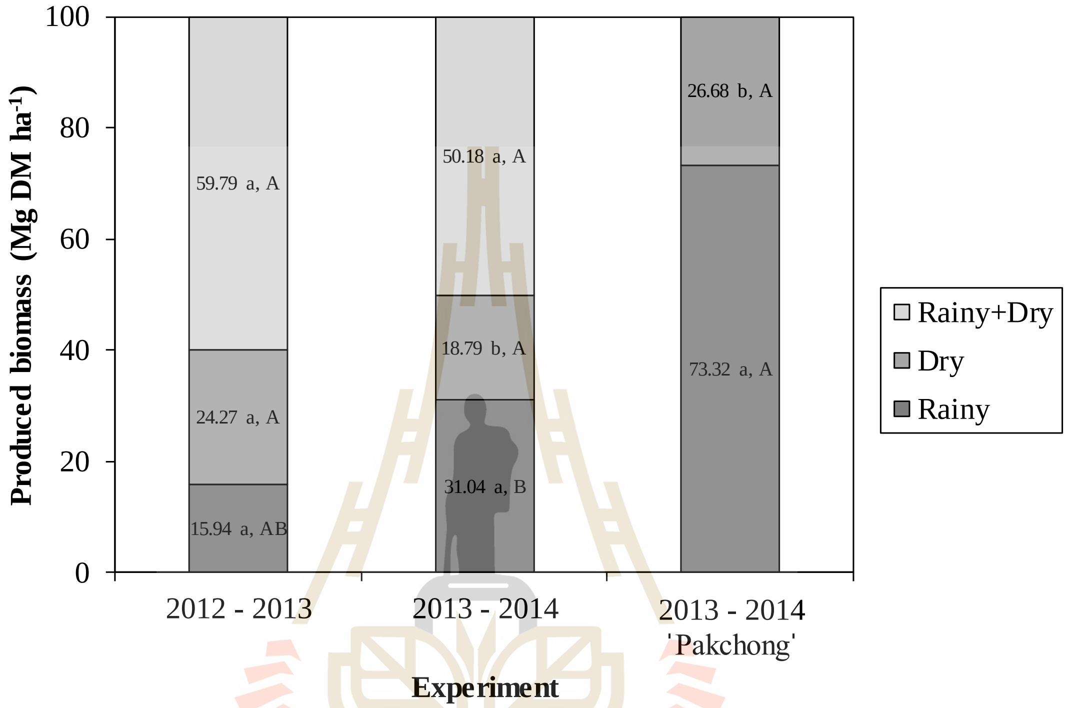



**Figure 4.14** **Relative distribution and effect of season on biomass production. Means in the same experiment followed by the same lowercase letter are not significantly different. Means in the same season followed by the same uppercase letter are not significantly different.**

**Table 4.20 Effect of late planting of setts on DM yield.**

| | Mg DM ha$^{-1}$ | |
|---|---|---|
| | Entry 6 | |
| Experimental | 2012 - 2013 | 2013 - 2014 |
| Yield | 2.16 A | 1.40 A |

Means followed by the same uppercase letter within a row are not significantly different.

**Table 4.21 Results of ANOVA to test for effects of the experimental year on agronomically important development parameters at the end of the rainy-season planting of Napier grass in 2012 and 2013.**

| Explanatory factor | Entry 6 |
|---|---|
| Seedling rate | $F(1,4) = 5.37$, $P < 0.081$ n.s. |
| Tiller | $F(1,4) = 5.22$, $P < 0.084$ n.s. |
| Height | $F(1,4) = 1.54$, $P < 0.281$ n.s. |
| LAI | $F(1,4) = 10.25$, $\boldsymbol{P < 0.032}$***** |

n.s.= not significant, *= sig. at 5%. *P*-values < 0.05 are shown in bold.

### 4.7.1 Summary of the Experiment

The results proved that Napier grass crops for biomass production can be cropped under minimum inputs, as practiced by the natural farming system. Therefore the conventional cropping system must be fundamentally altered. Based on these results, the least-altered cropping system for Napier grass (initiation by setts, frequent intercutting intervals and inception in May) bore the lowest DM yields and, thus, showed limited potential for the natural farming system. Additionally, setts, such as the propagule preferred for Napier grass crop initiation, thrived in the experimental year 2013-2014 in which more rainfall was measured and, thus, should be preferably cultivated in areas of sufficient annual rainfall. The effects of increasing sett densities (4 to 18 were tested) or planting method (horizontal burying or vertical insertion) on biomass production were not found, hence, reduced initiation density and handling on the field, vertical insertion may be the most practical approach.

Although reducing the initiation densities of various cutting types showed no effect on DM yields, reduced initiation inputs improved the input:output ratio and are, thus, more profitable. Longer stem sections with more nodes (60, 100 and 120 cm stem sections) tended to bear more biomass than setts.

However, in the experiment in 2012 until 2013, a fundamentally altered cropping system (consisting of terminal cutting, single-cut instead of ratooning) stood out with 16.14 Mg DM $ha^{-1}$. Although this DM yield could not be replicated in successive experiments, terminal cuttings continuously produced the highest yields and had a productive input:output ratio and, thus, proved to be the best propagule for the natural farming system. Moreover, terminal cuttings showed a high ratooning incompatibility and should be planted in a single-cut interval.

Reduced DM yields at an immeasurably low level at the final interval were the result of a four-monthly intercutting interval irrespective of cutting type. Intercutting intervals of 6 or 12 months had no effect on the cumulated DM yield of stem-section cuttings even though entries produced continuously less biomass, and even less during the dry season. The planting date (at the beginning or end of the rainy season) of setts had no significant effect on produced biomass. The late planting date of plots produced insignificantly more biomass during the dry season than equivalents during the rainy season (in contrast to DM yields that decreased with ratooning in the dry season) and showed a promising potential as a dry-season crop which, subsequently, would enable year-round cropping.

## 4.8 Summary of Treatments and Farming Systems

### 4.8.1 Biomass Yield

In conventional farming practice, additional irrigation and fertilization is applied directly after field planting to enable the best germination of Napier grass. In the present study, Napier grass was produced under natural conditions and additional irrigation and fertilization was omitted completely. Biomass (0.6 to 16 Mg DM $ha^{-1}$ $yr^{-1}$) was produced solely under rainfed conditions (811 and 1352 mm precipitation) and the rooting rates ranged between 8 to 24% (except for entry 6 planted in September with 20 and 34%). Biomass production from Napier grass responded significantly to fertilization, widely described in literature, and thus, reduced yields were expected under tested conditions of limited fertility (Norsuwan and Marohn, 2014). Nevertheless, yields from the present investigations were very consistent with the yields of other studies under similar conditions. In western Cuba, DM yields of unfertilized Napier grass crops ranged from 3.50 to 10.75 Mg $ha^{-1}$ under rainfed conditions (Herrera, 2016). A study conducted in the Chiang Mai area produced 2.34 Mg DM $ha^{-1}$ without additional fertilization and 4.34 Mg DM $ha^{-1}$ under rainfed conditions during the dry season (November until May) (Norsuwan and Marohn, 2014). Knoll et al. found in a study conducted in Tifton/USA, a yield decrease of unfertilized Napier grass (from 36.3 to 5.0 Mg DM $ha^{-1}$ $yr^{-1}$) during four successive years (Knoll et al., 2011).

### 4.8.2 Cutting Type

#### 4.8.2.1 Terminal Cuttings

The highest DM yields were produced by terminal cuttings. The successful propagation of tall grasses by terminal cuttings is scarcely reported in literature as this technique is hardly practiced in industrial cropping systems. Nevertheless, the good rooting of terminal cuttings is somehow consistent with reports from other studies in which sugarcane setts from upper-positioned stem portions rooted more successfully than lower portions (Kolo et al., 2005; Sime, 2013). In contrast, cuttings taken from the lower portion of Napier grass stems were superior to younger material from the upper portion (Knoll and Anderson, 2012). However, multiple factors have effects on successful propagation, particularly the maturity of terminal shoots when used as propagation material (Hartmann et al., 2013). Young terminal cuttings, up to 6 months old, are usually soft and, thus, deemed non-rootable as the for the regrowth important primordia differentiates with ripening (Druse, 2012). We observed that the leaf sheaths covered the cane for several months before falling off and collected water from rain and condensation. The collected water stimulated root-primordia growth on the cane of the mother plant. Thus, matured terminal cuttings most often already have roots although not being a completely developed liner. The rudimentarily initiated roots begin to grow quickly after planting and develop the terminal cutting much faster into a plantlet than un-rooted stem-section cuttings.

#### 4.8.2.2 Planting Method and Density of Setts

Each crop initiation of Napier grass, as described, uses stem-section cuttings. Local farmers recommend starting Napier grass crops with a density of one sett per square meter (approx. 15 cm long with two nodes) at an angle and one node exposed because setts bear more cuttings per cane and root reliably under supplemental irrigation. A previous study, under greenhouse conditions, has shown effects on the planting method (vertical or horizontal) of setts to establish Napier grass whereas vertically inserted setts had the highest number of shoots and shoot mass. In consequence, the authors of the study recommended vertical planting would result in a more superior establishment than horizontal burying (Knoll and Anderson, 2012). In conflict with this recommendation, repeated statistically insignificant differences in the planting method of setts were found under field conditions during the full experiment. Interestingly, the number of nodes in the ground evidenced more effect on yield despite the planting method, i.e. eighteen nodes per square meter from nine horizontal planted setts or from eighteen single nodes of vertically inserted twin-setts produced 1.01 and 1.09 Mg DM $ha^{-1}$ after a growing period of six months the during first experiment (i.e. entries 7 and 16, Table 4.4). In comparison, nine nodes in the ground from vertically inserted single setts produced 0.54 Mg DM $ha^{-1}$, and, consequently, half the expected yield (entry 15, Table 4.4). Seedling rates of 11.74 and 14.90% (entry 7), 13.27 and 21.91% (entry 15) as well as 9.57 and 16.20% (entry 16) were evaluated in the first and second years (Tables 4.8 and 4.13). The steady seedling rate of cuttings of the present in-situ experiment contrasts with the findings of Knoll and Anderson who found significantly less viable cuttings from horizontally planted (57.5%) than from vertically inserted cuttings (85%) under controlled greenhouse conditions (Knoll and Anderson, 2012). On the other hand, the recent findings of insignificant differences between vertical or horizontal planting are very consistent with previously reported findings from literature (Ssekabembe, 1998).

#### 4.8.2.3 Long Stem Sections

A study on sugarcane cultivation under tropical conditions reports the planting of whole canes bringing higher yields and reducing planting costs in contrast to planting setts (Hsu and Kao, 1981). It was observed that long canes of sugarcane or Napier grass are preferred, moreover, for crop indication under unfavorable field conditions in Thailand, when following general recommendations for reliable sprouting success (Viator et al., 2005). However, detailed investigations of different propagation methods for tall grasses, including effects on DM yield, are scarcely reported. Nevertheless, in the present study, higher DM yield as well as more vigorous sprouting was expected from long-stem sections than from setts due to the higher reserve content and increased buds for reproduction. These expectations are consistent with a previous report of better propagation success (37%) and subsequently significantly higher yields (43%) with increasing nodes-per-stem section of Napier grass crops (Ramadhan, Njunie and Lewa, 2015). According to expectations, longer stem sections tended to produce more biomass than the shorter setts during the full experiment (Tables 4.15 and 4.18). However, the stem-produced FM yield was only slightly higher than the biomass needed for initiation, relativizing higher biomass yields and showing only small benefits for biomass production in this experiment (Figures 4.5, 4.9 and 4.12).

Interestingly, seedling rate, expressed as the relation between counted sprouted buds and the absolute number of buds in the ground per square meter, was found the same as the ratio of setts. The higher biomass yield from long stem sections is ascribed to other favorable agronomic parameters such as the number of tillers and their height. Indeed, both parameters were evaluated as highest during the first and second investigations, where evaluated entries 11 and 13 bore the most and tallest tillers per plant (Tables 4.8 and 4.13). Previous studies found correlations between DM yield and tiller number, maturity and plant height (Purbajanti, Anwar and Kusmiyati Widyati, 2012; Zewdu, 2008). Thus, the DM yields of these two entries resulted from tillers and stem height, also consistent with a previous study which found stem height was strongly associated with total and stem dry-matter yields (Ferraris and Sinclair, 1980). Additionally, the results corroborate those of several previous studies which have shown DM production increased with maturity and plant architecture (stem and tiller formation) by lignification (Aganga et al., 2005; Jorgensen et al., 2010). The vigorous sprouting of buds of long stem-section cuttings is attributed to energy-rich reserves, conserved as stem structures, which let buds profit differently intense from translocation effects. Translocation effects for bud-break initiation and subsequent tussock forming for lateral soil occupation are described in literature (Beaty, Engel and Powell, 1978; Slewinski, 2012). Last, but not least, intercutting intervals and subsequent regrowth affected biomass production from stem sections with increasing length in the same way as with setts.

### 4.8.3 Cutting Regime

An optimized cutting regime (i.e. cutting height and frequency) is important for biomass increase and long-time management of Napier grass plantations. Cutting regimes of 35 days at 15 cm height are found best under conventional management (Wijitphan, Lorwilai and Arkaseang, 2009a). On the contrary, three-monthly harvest frequencies and a cutting height of 15 cm were found best for less intensely managed Napier grass crops (Rengsirikul et al., 2011). Hence, less frequent ratooning intervals of four months were chosen for the present experiments as slower production of biomass was expected due to the reduced management. The DM yield of setts (entry 5, horizontal 15 cm) was much lower after a growing period of four months than expected from literature review, signaling that increased periods of uninterrupted growing were favored. Otherwise, insignificant effects on produced biomass of various long-stem sections and various long intercutting intervals (4, 8 and 12-monthly) were found, proving yields did not increase significantly with increasing time periods or being negatively affected by the ratooning technique itself, which is consistent with other reports (Butt et al., 1993). The small quantity of biomass produced is attributed to deficient nutrients, in particular N, a fact also corroborated by the low germination rates of stem-section cuttings, due to the effect of germination increase by additional N fertilization after planting (Tables 4.8 and 4.13). However, significant yield differences between stem-section cuttings and terminal cuttings revealed cutting-type effects on produced biomass after four months (Table 4.3). Terminal cuttings showed a significant yield decline due to intercutting intervals, attributed to a ratooning intolerance, proving a twelve-monthly single-cut management for highest yield production. All cutting types increased yields with successive age and maturity (tussock and stalk formation), consistent with literature reports (Lounglawan, Lounglawan and Suksombat, 2014; Manyawu et al., 2003). Apparently, yield decline after ratooning in January (during the dry season) was, consequently, found during the full experiment and negative effects from ratooning during the dry season are coherent with other reports (Tudsri et al., 2002).

### 4.8.4 Planting Date

There are two seasons in Thailand which dominate domestic rainfed farm management. Heavy rainfall and beneficial weather before the beginning of the dry season prepare good planting conditions. Hence, after the dry season ends in May, farming activity begins and ends in September in accordance with precipitation decline. Due to the rough climate conditions (i.e. heat, drought) during the dry season, Napier grass stands must be established and hardened to endure the risks of dry season die-off due to water deficiency. Reports to benefit cropping during the dry season in Thailand are lacking as a consequence. Significant effects on the planting date, in particular before fall/winter changes, are reported from previous investigations (Knoll and Anderson, 2012; Viator et al., 2005). Hence, in the present investigation, regular and late-date planting was investigated (Table 3.2). In the rough climate during the dry season smaller biomass yields were expected from crops planted at the beginning of the dry season (Rengsirikul et al., 2013; Tudsri et al., 2002). Interestingly, an unclear pattern was found where late-date planted entry 6 produced higher yields in first experiment and smaller yields during the second experiment than equivalents initiated in May (Tables 4.7 and 4.12). Besides smaller yields, also meager growth parameters were expected. In contrast to the expectations, entry 6 showed a higher seedling rate (21.81 and 33.91%) than equivalents from regular planting (11.25 to 17.65%), shown in Tables 4.8 and 4.13, resulting in insignificant differences in produced biomass. An observation from fall-planted Napier grass, reported only 13.9% emergence from 2$^{nd}$ November and none from 15$^{th}$-November-planted cuttings (Knoll and Anderson, 2012). Besides having the best seedling rate, entry 6 grew much taller than the other entries, with 47.85cm, bearing stems for higher yield during the first experiment. Hence, the tendency of yield increase of entry 6 during the first experiment is consistent with the observations of Viator et al., who also found increasing yields from sugarcane billets (=setts) planted at a late date (Viator et al., 2005). In this experiment, both patterns are attributed to a moderate rainy season and heavy rainfall that introduced the dry season in September (Figure 4.1). In conclusion, planting Napier grass at a late date in September presented options for biomass production and profitable for land-use efficiency.

# CHAPTER V

# CONCLUSIONS

## 5.1 Conclusions

Setts are commonly preferred for Napier grass crop initiation in Thailand. On the one hand, setts appeared very unproductive under water deficit and, on the other hand, setts showed a very profitable input:output ratio under increasing rainfall in the present experiment. Based on these results, it is recommended that setts, as initiation propagules, should be preferred in rainy regions or in farming systems with supplemental inputs such as additional irrigation. According to literature reports, besides by additional irrigation, DM yields can be multiplied by simultaneous additional fertilization as practiced in the conventional farming system. Horizontal burying or vertical inserting of setts was observed to have no significant effect on biomass yield, hence, ease of planting and handling in the field may prefer vertical insertion. Furthermore, Napier grass as the dry-season crop or intercrop during the dry season instead of letting fields lie fallow can be recommended. Hitherto, terminal cuttings were unknown propagules for industrial biomass production, even more remarkable, terminal cuttings produced the highest biomass yield including best input:output ratio. Thus, the cuttings would be entirely recommendable as propagules even though not as many propagules can be won from whole stalks as from setts. Last but not least, planting of whole stems cannot be recommend as the biomass input: output ratio, stand establishment in the field, ease of planting and agronomic parameters are not preferential.

Napier grass crops, from initiation to stand, developed much more slowly under natural conditions than observed for conventionally managed crops. Longer intercutting intervals or single-cut systems are recommended. In return, frequent intercutting intervals showed no yield-increasing effects, indeed, crops consisting of terminal cuttings should only be managed in a single-cut system. Nevertheless, higher initiation densities, irrespective of cutting type, tended to increase yield but should only be practiced if farm land is limited.

As a general conclusion, fallow land due to water scarcity in the Nakhon Ratchasima Province can be avoided by Napier grass planting for biomass under natural farming if the recommended farming system is followed. Farmers' individual capabilities will decide whether full-year cropping of Napier grass by the natural farming system or cropping as a patch crop during the dry season is best.

## 5.2 Recommendations for Future Work

Further experiments envisaging the optimization of the natural farming system can show the full biomass potential of Napier grass with regard to improved input:output ratio as an increased biomass yield potential is assumed for cultivars. Besides the seedling rate, tiller recruitment is another important agronomic parameter with direct effect on biomass production. Hence, both parameters are affected by a better N supply, a matter worth investigating. A better N supply for fields could be reached, for example, by green manure. As a further approach for improved biomass production, the cropping of Napier grass with other crops could show profitable interaction effects. Some beneficial interactive crop members from the legume family such as peas or beans are able to fix air nitrogen in the roots for biomass production and would remain as green manure on the field after the harvest. The main focus of this experiment was to examine a full cropping system for Napier grass under natural conditions. However, this experiment could not cover a full cropping strategy. As mentioned above, terminal cuttings are recommended propagules even if not many can be won from stalks. Hence, it was necessary to investigate the best strategy for the most efficient nursery production of propagules and balance that with biomass seasonal production. It would be further worthwhile to investigate further economical propagule production methods such as whether terminal cuttings should be cropped primarily during the rainy season and to use setts with their ability to produce tillers during the dry season to produce new terminal cuttings for the next year.

# REFERENCES


Aganga, A.A., Omphile, U.J., Thema, T., and Baitshotlhi, J.C. (2005). Chemical composition of Napier grass (Pennisetum purpureum) at different stages of growth and Napier grass silages with additives. **Journal of Biological Sciences**, 5(4): 493-496.

Aldrich, R.J. (1984). **Weed-crop ecology: Principles in weed management.** Breton, North Scituate, 465p.

Amon, T., Gruber, W., Hoffstede, U., Jäger, P., Jäkel, K., Kaiser, F., Keymer, U., Linke, B., Berettig-Bruns, U. and Niebaum, A. (2010). **Gasausbeute in landwirtschaftichen Biogasanlagen.** 2nd ed. KTBL, Kassel, 36p.

Ansah, T., Osafo, E.L.K., and Hansen, H.H. (2010). Herbage yield and chemical composition of four varieties of Napier (Pennisetum purpureum) grass harvested at three different days after planting. **Agriculture and Biology Journal of North America**, 1(5): 923-929.

Arjharn, W., Hinsui, T., Liplap, P., and Raghavan, G.S. (2012). Evaluation of electricity production from different biomass feedstocks using a pilot-scale downdraft gasifier. **Journal of Biobased Materials and Bioenergy**, 6(3): 309-318.

Arjharn, W., Kongkrapee, N., Rubsombut, K., Chanaroke, P., and Hinsui, T. (2008). Study of a small scale biomass power plant for rural communities evaluation of performance and their pollution. **Journal of the National Research Council of Thailand (Natural Science)(Thailand),** 40(2): 127-146.

Ashraf, M., and Harris, P.J.C. (2013). Photosynthesis under stressful environments: An overview. **Photosynthetica**, 51(2): 163-190.

Assanee, N., and Boonwan, C. (2011). State of The Art of Biomass Gasification Power Plants in Thailand. **Energy Procedia**, 9: 299-305.

Bakker, H. (1999). **Sugar cane cultivation and management.** Springer, Boston, 679p.

Barz, M., and Delivand, M.K. (2011). Agricultural residues as promising biofuels for biomass power generation in Thailand. **Journal of Sustainable Energy & Environment**, Special Issue 2011: 21-27.

Bassam, N.E. (2010). **Handbook of bioenergy crops: A complete reference to species, development and applications.** Earthscan, London, 544p.

Bayble, T., Melaku, S., and Prasad, N.K. (2007). Effects of cutting dates on nutritive value of Napier (Pennisetum purpureum) grass planted sole and in association with Desmodium (Desmodium intortum) or Lablab (Lablab purpureus). **Livestock Research for Rural Development**, 19(1): 120-136.

Beaty, E. R., Engel, J. L., and Powell, J. D. (1978). Tiller development and growth in switchgrass. **Journal of Range Management**, 31(5): 361-365.

Beeman, R. S. and Pritchard, J.A. (2001). **A green and permanent land: Ecology and agriculture in the Twentieth Century.** Lawrence, University Press of Kansas, 232p.

Biala, K., Terres, J.-M., Pointereau, P., and Paracchini, M. L. (2007). Low input farming systems: an opportunity to develop sustainable agriculture. **Proceedings of the JRC Summer University Ranco**; 2-5 July, 2007 Ispra, Italy.

Bräuchler, C., Meimberg, H., and Heubl, G. (2004). Molecular phylogeny of the genera Digitalis L. and Isoplexis (Lindley) Loudon (Veronicaceae) based on ITS-and trnL-F sequences. **Plant Systematics and Evolution**, 248(1-4): 111-128.

Bräuchler, C., Meimberg, H., and Heubl, G. (2010). Molecular phylogeny of Menthinae (Lamiaceae, Nepetoideae, Mentheae)–taxonomy, biogeography and conflicts. **Molecular Phylogenetics and Evolution**, 55(2): 501-523.

Briske, D.D. (1991). Developmental morphology and physiology of grasses. In: **Grazing management: An ecological perspective**. Heitschmidt, R.K,. and Stuth J.W., (eds.). Timber Press, Portland, p. 85-108.

BSA (Ed.). (2000). **Richtlinien für die Durchführung von landwirtschaftlichen Wertprüfungen und Sortenversuchen**. Landbuch-Verlag, Hannover, 348p.

Burtt-Davy, J. (1915). Napier grass: A new and valuable fodder-grass for South Africa. **Agriculture Journal of South Africa**, 1(4): 362-366.

Butt, N.M., Donart, G.B., Southward, M.G., Pieper, R.D., and Mohammad, N. (1993). Effect of defoliation on harvested yield of napier grass. **Pakistan Journal of Agricultural Research**, 14(4): 366-372.

Casler, M.D., Vermerris, W., and Dixon, R.A. (2015). Replication concepts for bioenergy research experiments. **BioEnergy Research**, 8(1): 1-16.

Chainuvati, C., and Athipanan, W. (2001). Crop diversification in Thailand. In: **Crop diversification in the Asia-Pacific region.** Papademetriou, M.K,. and Dent, F.J., (eds). FAO, Bangkok, Thailand, p. 130-146.

Chanthunyagarn, S., Garivait, S., and Gheewala, S. H. (2004). Bioenergy atlas of agricultural residues in Thailand. **Joint International Conference on**

**Sustainable Energy and Environment (SEE)**; 1-3 December, 2004; Hua Hin, Thailand. p. 334-339.

Chen, C.S., Wang, S.M., and Hsu, J.T. (2006). Factors affecting in vitro true digestibility of napiergrass. **Asian-Australasian Journal of Animal Sciences**, 19(4): 507-513.

Clavero, T. (1997). Tiller dynamic of dwarf elephantgrass (Pennisetum purpureum cv. Mott) under defoliation. **XVIII International Grassland Congress**; 8-19 June, 1997; Winnipeg, Canada. NO. 345, p. 22-31.

Cutts, G.S., Webster, T.M., Grey, T.L., Vencill, W.K., Dewey Lee, R., Tubbs, R.S., and Anderson, W.F. (2011). Herbicide effect on Napiergrass (Pennisetum purpureum) control. **Weed Science**, 59(2): 255-262.

Dahiya, A. (2014). **Bioenergy: Biomass to Biofuels**. Academic Press, UK, 681p.

Dambroth, M., and El Bassam, N. (1983). Low input varieties: definition, ecological requirements and selection. In: **Genetic aspects of plant nutrition.** Saric, M.R., and Loughman, B.C., (eds). Springer, Netherlands, p. 409-421.

Da Silva, S.C., Sbrissia, A.F., and Pereira, L.E.T. (2015). Ecophysiology of C4 forage grasses - Understanding plant growth for optimising their use and management. **Agriculture**, 5(3): 598-625.

De Groot, R. (2006). Function-analysis and valuation as a tool to assess land use conflicts in planning for sustainable, multi-functional landscapes. **Landscape and Urban Planning**, 75(3): 175-186.

Demirbaş, A. (2001a). Biomass resource facilities and biomass conversion processing for fuels and chemicals. **Energy Conversion and Management**, 42(11): 1357-1378.

Demirbaş, A. (2001b). Yields of hydrogen-rich gaseous products via pyrolysis from selected biomass samples. **Fuel**, 80(13): 1885-1891.

De Morais, R.F., de Souza, B.J., Leite, J.M., de Soares, L.H. B., Alves, B.J.R., Boddey, R.M., and Urquiaga, S. (2009). Elephant grass genotypes for bioenergy production by direct biomass combustion. **Pesquisa Agropecuária Brasileira**, 44(2): 133-140.

De Morais, R.F., Quesada, D.M., Reis, V.M., Urquiaga, S., Alves, B.J., and Boddey, R. M. (2012). Contribution of biological nitrogen fixation to Elephant grass (Pennisetum purpureum Schum.). **Plant and Soil**, 356(1-2): 23-34.

Dent, D., Elliott, N.C., Farrell, J.A., Gutierrez, A.P., Lenteren, J.C. van, Walton, M.P., and Wratten, S. (1995). **Integrated Pest Management**. Springer, London, 356p.

Department of Alternative Energy Development and Efficiency. (2016). Energy in Thailand: Facts & Figures 2013 Thailand: DAEDE. Available from http://weben.dede.go.th/webmax/ Accessed date: Aug 24, 2016.

Druse, K. (2012). **Making more plants: The science, art, and joy of propagation.** Stewart, Tabori & Chang, New York, 256 p.

Elbersen, B.S., and Andersen, E. (2008). Low-input farming systems: Their general characteristics, identification and quantification. In: **Low input farming systems: an opportunity to develop sustainable agriculture**. Biala, K., Terres, J.-M., Pointereau, P., and Paracchini, M. L. (eds). Proceedings of the JRC Summer University Ranco; 2-5 July, 2007 Ispra, Italy, p. 12-21.

Farrell, G., Simons, S.A., and Hillocks, R.J. (2002). Pests, diseases and weeds of Napier grass, Pennisetum purpureum: A review. **International Journal of Pest Management**, 48(1): 39-48.

Federal Ministry of Food and Agriculture. (2009). Förderprogramm für den Export deutscher Unternehmen der Agrar- und Ernährungswirtschaft - Exportförderung des BMEL. Berlin: BMEL. Available from: www.agrarexportfoerderung.de/fileadmin/sites/default/files/Thailand_02.pdf. Accessed date: Aug 23, 2016.

Ferraris, R. (1980). Effect of harvest interval, nitrogen rates and application times on Pennisetum purpureum grown as an agroindustrial crop. **Field Crops Research**, 3: 109-120.

Ferraris, R., and Sinclair, D. (1980). Factors affecting the growth of Pennisetum purpureum in the wet tropics. II. Uninterrupted growth. **Australian Journal of Agricultural Research**, 31(5): 915-925.

Garivait, S., Chaiyo, U., Patumsawad, S., and Deakhuntod, J. (2006). Physical and chemical properties of Thai biomass fuels from agricultural residues. **The 2nd Joint International Conference on "Sustainable Energy and Environment (SEE 2006)"**; 1-23 November, 2006; Bangkok, Thailand, p. 1-23.

Gomide, C.A., Chaves, C.S., Ribeiro, K.G., Sollenberger, L.E., Paciullo, D.S., Pereira, T.P., and Morenz, M.J. (2015). Structural traits of elephant grass (Pennisetum purpureum Schum.) genotypes under rotational stocking strategies. **African Journal of Range & Forage Science**, 32(1): 51-57.

Hakansson, S. (2003). **Weeds and weed management on arable land: An ecological approach.** CABI publishing, Wallingford, 288p.

Hartmann, H.T., Kester, D.E., Davies, F.T., and Geneve, R. (2013). **Hartmann & Kester's plant propagation: Principles and practices.** 8th revised ed. Pearson Education Limited, Harlow, 928p.

Herrera, R.S. (2016). Clones of Pennisetum purpureum for different ecosystems and productive purposes. **Cuban Journal of Agricultural Science**, 49(4): 515-519.

Hill, D.S. (2008). **Pests of crops in warmer climates and their control.** Springer, Netherlands, 720p.

Ho, P.H. (1999). **An illustrated flora of Vietnam (Vols. 1–3).** Young Publishing House, Hó Chí Minh, 2943p.

Horvath, D.P., Anderson, J.V., Chao, W.S., and Foley, M.E. (2003). Knowing when to grow: Signals regulating bud dormancy. **Trends in Plant Science**, 8(11): 534-540.

Hsu, E.R.H., and Kao, Y.C. (1981). Review on sugarcane planting using whole-stalk seed cane in Huwei District Sugar Factory. **Journal of the Agricultural Association of China**, (81): 42-50.

Humbert, R.P. (1963). **The growing of sugar cane.** Elsevier Publishing Co., Amsterdam, 711p.

Johansson, T.B., Patwardhan, A.P., Nakićenović, N., and Gomez-Echeverri, L. (Eds.). (2012). **Global energy assessment: Toward a sustainable future.** Cambridge University Press, Cambridge, 1182p.

Johl, S.S. (Ed.). (1979). **Irrigation and agricultural development.** Pergamon Press, Oxford, 380p.

Johnson, W.L., Guerrero, J., and Pezo, D. (1973). Cell-Wall constituents and In Vitro digestibility of Napier grass (Pennisetum Purpureum). **Journal of Animal Science**, 37(5): 1255-1261.

Jorgensen, S.T., Pookpakdi, A., Tudsri, S., Stölen, O., Ortiz, R., and Christiansen, J.L. (2010). Cultivar-by-cutting height interactions in Napier grass (Pennisetum purpureum Schumach) grown in a tropical rain-fed environment. **Acta Agriculturae Scandinavica, Section B- Soil & Plant Science**, 60(3): 199-210.

Kennedy, P.B. (1919, March 29). A new forage plant---Napier fodder. **Pacific Rural Press**, California, USA, p. 478.

Knoll, J.E., and Anderson, W.F. (2012). Vegetative propagation of Napiergrass and energycane for biomass production in the Southeastern United States. **Agronomy Journal**, 104(2): 518-522.

Knoll, J.E., Anderson, W.F., Strickland, T.C., Hubbard, R.K., and Malik, R. (2011). Low-input production of biomass from perennial grasses in the coastal plain of Georgia, USA. **Bioenergy Research**, 5(1): 206-214.

Kolo, I.N., Adesiyun, A.A., Misari, S.M., and Ishaq, M.N. (2005). Evaluation of top, middle and bottom stalk of Sugarcane as planting material. **Sugar Tech**, 7(2-3): 89-92.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., and Rubel, F. (2006). World map of the Köppen-Geiger climate classification updated. **Meteorologische Zeitschrift**, 15(3): 259-263.

Kubota, F., Matsuda, Y., Agata, W., and Nada, K. (1994). The relationship between canopy structure and high productivity in napier grass, Pennisetum purpureum Schumach. **Field Crops Research**, 38(2): 105-110.

Lal, R. (2001). Soil degradation by erosion. **Land Degradation & Development**, 12(6): 519-539.

Langer, R.H.M. (1979). **How Grasses Grow.** 2nd ed. Hodder, London, 70p.

Lemus, R., and Lal, R. (2005). Bioenergy crops and carbon sequestration. **Critical Reviews in Plant Sciences**, 24(1): 1-21.

Lewandowski, I., and Schmidt, U. (2006). Nitrogen, energy and land use efficiencies of miscanthus, reed canary grass and triticale as determined by the boundary line approach. **Agriculture, Ecosystems & Environment**, 112(4): 335-346.

Lichtfouse, E., Navarrete, M., Debaeke, P., Souchère, V., Alberola, C., and Ménassieu, J. (Eds.) (2009). **Sustainable Agriculture**. Springer, Netherlands, 929p.

Longpichai, O. (2013). Determinants of adoption of crop diversification by smallholder rubber producers in Southern Thailand: Implications on natural resource conservation. **Kasetsart Journal (Soc. Sci)**, 34: 370-382.

Lounglawan, P., Lounglawan, W., and Suksombat, W. (2014). Effect of cutting interval and cutting height on yield and chemical composition of King Napier grass (Pennisetum purpureum x Pennisetum americanum). **APCBEE Procedia**, 8: 27-31.

Mani-in, P., Thobunluepop, P., Tonmukayakul, N., ChangKaewmanee, J., Muangpan, J., and Pongtip, A. (2014). การเจริญเติบโตผลผลิตชีวมวล และก๊าซชีวภาพต่อการจัด

ระยะปลูกหญ้าเขตร้อน 7 พันธุ์ Growth Biomass and Biogas Production of Seven Tropical Grasses under Different Crop Spacing. **Agricultural Science Journal**, *45*(2): 457-460.

Manyawu, G.J., Chakoma, C., Sibanda, S., Mutisi, C., and Chakoma, I.C. (2003). The effect of harvesting interval on herbage yield and nutritive value of Napier grass and hybrid Pennisetums. **Asian-Australasian Journal of Animal Sciences**, 16(7): 996-1002.

Meteorological Department (Ed.). (2012). The climate of Thailand. Climatological Group. **Meteorological Development Bureau.** Bangkok, Thailand. Available from www.tmd.go.th/en/downloads.php. Accessed date: Feb 20, 2016.

Ministry of Energy and Electricity Generating Authority of Thailand. (2016). **Thailand Power Development Plan**. Bangkok: EPPO. Available from http://www.eppo.go.th/index.php/en/policy-and-plan/en-tieb/tieb-pdp. Accessed date: Aug 24, 2016.

Miyagi, E. (1980). The effect of planting density on yield of Napier grass (Pennisetum purpureum Schumach). **Science Bulletin of the College of Agriculture, University of the Ryukyus**, (27): 293-301.

Mohammed, I.Y., Abakr, Y.A., Kazi, F.K., Yusuf, S., Alshareef, I., and Chin, S.A. (2015). Pyrolysis of Napier grass in a fixed bed reactor: effect of operating conditions on product yields and characteristics. **BioResources**, 10(4): 6457-6478.

Mohammed, I.Y., Abakr, Y.A., Kazi, F.K., Yusup, S., Alshareef, I., and Chin, S.A. (2015). Comprehensive characterization of Napier grass as a feedstock for thermochemical conversion. **Energies**, 8(5): 3403-3417.

Moore, K.J. (2008). Herbaceous biomass: state of the art. USDA 2008: **Proceedings of the Short Rotation Crops International Conference GTR-NRS-P;** July 31, 2008; 31: 39.

Morrison, I.M. (1980). Changes in the lignin and hemicellulose concentrations of ten varieties of temperate grasses with increasing maturity. **Grass and Forage Science**, 35(4): 287-293.

Munzert, M. (1992). **Einführung in das pflanzenbauliche Versuchswesen: Grundlagen und Praxis des Versuchswesens im landwirtschaftlichen, gärtnerischen und forstwirtschaftlichen Pflanzenbau**. Parey, Berlin , 163p.

Nagasuga, K. (2005). Acclimation of biomass productivity to light intensity in napiergrass (Pennisetum purpureum Schumach.) plant. **Bulletin of the Institute of Tropical Agriculture, Kyushu University**, 28(2): 15-20.

National Energy Policy Council. (2014). **10-year alternative energy development plan (2012-2021)**. Bangkok: NEPC. Available from http://weben.dede.go.th/webmax/content/napier-grass. Accessed date: Nov 16, 2014.

National Statistical Office. (2013). **2013 Agricultural Census**. Bangkok: Ministry of Information and Communication Technology. Available from http://web.nso.go.th/en/census/agricult/cen_agri03.htm. Accessed date: Aug 22, 2016.

Norsuwan, T., and Marohn, C. (2014). Effects of irrigation treatments and nitrogen applications in Napier grass planted in dry season as energy crop at Chiang Mai province. **Khon Kaen Agriculture Journal**, 42 (Suppl 2): 1-7.

Ohimain, E.I., Kendabie, P., and Nwachukwu, R.E. (2014). Bioenergy potentials of elephantgrass, Pennisetum purpureum Schumach. **Annual Research & Review in Biology**, 4(13): 2215-2227.

Panklib, T., Thaicham, P., and Khummongkol, D. (2016). Factors affecting agricultural residues used for energy in Thailand. **Energy Sources, Part A: Recovery, Utilization, and Environmental Effects**, 38(2): 236-242.

Papong, S., Yuvaniyama, C., Lohsomboon, P., and Malakul, P. (2004). Overview of

biomass utilization in Thailand. In: **The meeting for LCA in ASEAN Biomass Project, Japan** (Vol. 28).

Paterson, D.D. (1933). The influence of time of cutting on the growth, yield and composition of tropical fodder grasses I. Elephant grass (Pennisetum Purpureum). **The Journal of Agricultural Science**, 23(04): 615-641.

Payne, W.A. (2000). Optimizing crop water use in sparse stands of Pearl Millet. **Agronomy Journal**, 92(5): 808-814.

Pensupar, K. (2015). **The agricultural crop zoning system in Thailand**. Taiwan: FFTC. Available from http://ap.fftc.agnet.org/ap_db.php?id=400. Accessed date: Sep 12, 2016.

Pereira, L.E.T., Paiva, A.J., Geremia, E.V., and da Silva, S.C. (2015). Grazing management and tussock distribution in elephant grass. **Grass and Forage Science**, 70(3): 406-417.

Perfecto, I., Vandermeer, J., Hanson, P., and Cartín, V. (1997). Arthropod biodiversity loss and the transformation of a tropical agro-ecosystem. **Biodiversity and Conservation**, 6(7): 935-945.

Pholsen, S., Rodchum, P., Sommart, K., Ta-un, M., and Higgs, D.E.B. (2014). Dry matter yield and quality of forages derived from three grass species with and without legumes using organic production methods. **Khon Kaen Agriculture Journal**, 42(1): 65-80.

Pimentel, D., and Hall, C.W. (Eds.). (1984). **Food and Energy Resources**. Academic Press, Orlando, 287p.

Prasad, P.V.V., Staggenborg, S.A., and Ristic, Z. (2008). Impacts of drought and/or heat stress on physiological, developmental, growth, and yield processes of crop plants. In: **Response of crops to limited water: Understanding and modeling water stress effects on plant growth processes.** Ahuja, L.R., Reddy, V.R., Saseendran, S.A., and Yu Q. (eds.), American Society of Agronomy, USA, p. 301-355.

Prasertsan, S., and Sajjakulnukit, B. (2006). Biomass and biogas energy in Thailand: Potential, opportunity and barriers. **Renewable Energy**, 31(5): 599-610.

Purbajanti, E.D., Anwar, S., and Kusmiyati Widyati, F. (2012). Drought stress effect on morphology characters, water use efficiency, growth and yield of Guinea and Napier grasses. **International Research Journal of Plant Science**, 3(4): 47-53.

Quinn, L.D., Straker, K.C., Guo, J., Kim, S., Thapa, S., Kling, G., and Voigt, T.B. (2015). Stress-Tolerant feedstocks for sustainable bioenergy production on marginal land. **BioEnergy Research**, 8(3): 1081-1100.

Rahman, M.M., Ishii, Y., Niimi, M., and Kawamura, O. (2008). Effect of salinity stress on dry matter yield and oxalate content in Napiergrass (Pennisetum purpureum Schumach). **Asian-Australasian Journal of Animal Sciences**, 21(11): 1599-1603.

Rahman, M.M., Niimi, M., Ishii, Y., and Kawamura, O. (2006). Effects of season, variety and botanical fractions on oxalate content of napiergrass (Pennisetum purpureum Schumach). **Grassland Science**, 52(4): 161-166.

Ramadhan, A., Njunie, M.N., and Lewa, K.K. (2015). Effect of planting material and variety on productivity and survival of Napier grass (Pennisetum purpureum Schumach) in the coastal lowlands of Kenya. **East African Agricultural and Forestry Journal**, 81(1): 40-45.

Rao, K.V.M., Raghavendra, A.S., and Reddy, K.J. (2006). **Physiology and molecular biology of stress tolerance in plants**. 1st ed. Springer, Netherlands, 337p.

Rasul, G., and Thapa, G.B. (2003). Sustainability analysis of ecological and conventional agricultural systems in Bangladesh. **World Development**, 31(10):

1721-1741.

Ratchalēt, T., and Maxwell, J.F. (1994). **Weeds of soybean fields in Thailand.** Multiple Cropping Center, Faculty of Agriculture, Chiang Mai University, Chiang Mai, 408p.

Reda, A.G., Tripathi, N.K., and Mozumder, C. (2013). Agricultural landuse changes under climate variability in Thailand. **Open Science Repository Agriculture**, (open-access): e23050486.

Reddy, K.O., Maheswari, C.U., Reddy, D.J.P., and Rajulu, A.V. (2009). Thermal properties of Napier grass fibers. **Materials Letters**, 63(27): 2390-2392.

Rengsirikul, K., Ishii, Y., Kangvansaichol, K., Pripanapong, P., Sripichitt, P., Punsuvon, V., and Tudsri, S. (2011). Effects of inter-cutting interval on biomass yield, growth components and chemical composition of napiergrass (Pennisetum purpureum Schumach) cultivars as bioenergy crops in Thailand. **Grassland Science**, 57(3): 135-141.

Rengsirikul, K., Ishii, Y., Kangvansaichol, K., Sripichitt, P., Punsuvon, V., Vaithanomsat, P., and Tudsri, S. (2013). Biomass yield, chemical composition and potential Ethanol yields of 8 cultivars of Napiergrass (Pennisetum purpureum Schumach.) harvested 3-Monthly in Central Thailand. **Journal of Sustainable Bioenergy Systems**, 03(02): 107-112.

Rusland, G.A., Sollenberger, L.E., and Jones, C.S. (1993). Nitrogen fertilization effects on planting stock characteristics and establishment performance of Dwarf Elephantgrass. **Agronomy Journal**, 85(4): 857-861.

Sajjakulnukit, B., Yingyuad, R., Maneekhao, V., Pongnarintasut, V., Bhattacharya, S.C., and Abdul Salam, P. (2005). Assessment of sustainable energy potential of non-plantation biomass resources in Thailand. **Biomass and Bioenergy**, 29(3): 214-224.

Sarwar, M., (1999). Effect of nitrogen fertilization and stage of maturity of Mottgrss (Pennisetum purpureum) on its chemical composition, dry matter intake, ruminal characteristics and digestibility in Buffalo Bulls. **Asian-Australasian Journal of Animal Sciences**, 12(7): 1035-1039.

Schank, S.C., Chynoweth, D.P., Turick, C.E., and Mendoza, P.E. (1993). Napiergrass genotypes and plant parts for biomass energy. **Biomass and Bioenergy**, 4(1): 1-7.

Schulze, E.D., Beck, E., and Hohenstein, K.M. (2005). **Plant Ecology.** Springer, Berlin, 702p.

Sethaputra, S., Thanopanuwat, S., Kumpa, L., and Pattanee, S. (2001). Thailand's water vision: a case study. In: **From vision to action: A synthesis of experiences in Southeast Asia**. Ti, L.H. and Facon, T. (eds). Bangkok, FAO-ESCAP, p. 71-96.

Sime, M. (2013). The effect of different cane portions on sprouting, growth and yield of Sugarcane (Saccharum spp. L.). **International Journal of Scientific and Research Publications**, 3(1): 83-87.

Singh, B.P., Singh, H.P., and Obeng, E. (2013). Elephantgrass. In: **Biofuel crops: production, physiology and genetics**. B.P. Singh (ed). CABI Publishing, Wallingford, p. 271-291.

Singh, B.R., and Singh, D.P. (1995). Agronomic and physiological responses of sorghum, maize and pearl millet to irrigation. **Field Crops Research**, 42(2–3): 57-67.

Singh, P., Vijaya, D., Chinh, N.T., Pongkanjana, A., Prasad, K.S., Srinivas, K., and Wani, S.P. (2001). Potential productivity and yield gap of selected crops in the rainfed regions of India, Thailand, and Vietnam. **Natural Resource Management Program Report**, 5(ICRISAT): 27-32.

Slewinski, T.L. (2012). Non-structural carbohydrate partitioning in grass stems: a target to increase yield stability, stress tolerance, and biofuel production. **Journal of Experimental Botany**, 63(13): 4647-4670.

Smit, M.A., and Singels, A. (2006). The response of sugarcane canopy development to water stress. **Field Crops Research**, 98(2–3): 91-97.

Srisa-ard, K. (2007). Residual effects of applied chemical fertilisers on growth and seed yields of sunflower (Helianthus annuus cv. high sun 33) after the harvests of initial main crops of maize (Zea mays L.), soybean (Glycine max L.) and sunflower (Helianthus annuus). **Pakistan Journal of Biological Sciences**, 10(6): 959-963.

Ssekabembe, C.K. (1998). Effect of planting method on establishment of Napier grass varieties. **African Crop Science Journal**, 6(4): 407-416.

Stapf, O. (1912). Elephant Grass. A New Fodder Plant. (Pennisetum purpureum, Schum.). **Bulletin of Miscellaneous Information (Royal Botanic Gardens, Kew)**, (7): 309-316.

Steduto, P., Hsiao, T.C., Fereres, E., and Raes, D. (2012). Crop yield response to water. In: **Crop yield response to water.** FAO (ed). FAO, Roma, p. 144-153.

Stöcker, M. (2008). Biofuels and biomass-to-liquid fuels in the biorefinery: Catalytic conversion of lignocellulosic biomass using porous materials. **Angewandte Chemie International Edition**, 47(48): 9200-9211.

Strezov, V., Evans, T., and Hayman, C. (2008). Thermal conversion of elephant grass (Pennisetum purpureum Schum) to bio-gas, bio-oil and charcoal. **Bioresource Technology**, 99(17): 8394-8399.

Taberlet, P., Gielly, L., Pautou, G., and Bouvet, J. (1991). Universal primers for amplification of three non-coding regions of chloroplast DNA. **Plant Molecular Biology**, 17(5): 1105-1109.

Tekletsadik, T., Tudsri, S., Juntakool, S., and Prasanpanich, S.. (2004). Effect of dry season cutting management on subsequent forage yield and quality of Ruzi

(Brachiaria ruziziensis) and Dwarf Napier (Pennisetum purpureum L.) in Thailand. **Kasetsart Journal (Natural Science)**, 38: 457-467.

Tancho, A. (2008). **Applied Natural Farming (**เกษตรกรรมธรรมชาติประยุก). Mae Jo Natural Farming Information Center and National Science and Technology Development Agency, Pathom Thani.

Tancho, A. (2013). **Textbook in natural farming: principles, concepts & appropriate techniques in tropics**. Maejo Natural Farming information Center, Chiang Mai, 340p.

Tan, E. (2015). **Integrated Pest Management and Pest Control**. Callisto, New York, 334p.

Thanarak, P. (2012). Supply chain management of agricultural waste for biomass utilization and CO2 emission reduction in the lower northern region of Thailand. **Energy Procedia**, 14: 843-848.

The Government Public Relations Department. (2016). **Thailand's agricultural production to be in line with water resource management**. Bangkok: Foreign Office. Available from http://thailand.prd.go.th/ewt_news.php?nid=2702&filename=index. Accessed date: Sep 12, 2016.

The World Bank. (2016). **Gross domestic product 2015**. Washington: The World Bank. Available from https://www.databank.worldbank.org/data/download/GDP.pdf. Accessed date: Aug 23, 2016.

Thompson, J. B. (1919). **Napier and Merker grass : Two new forage crops for Florida (No 153)**. Gainesville, University of Florida Agricultural Experiment Station, p. 235-249.

Throm, G. (2007). **Grundlagen der Botanik.** 2nd ed. Nikol Verlagsgesellschaft, Hamburg, 428p.

Tomlinson, K.W., and O'Connor, T.G. (2004). Control of tiller recruitment in Bunchgrasses: Uniting physiology and ecology. **Functional Ecology**, 18(4): 489-496.

Topark-Ngarm, A., and Gutteridge, R.C. (1986). Forages in Thailand. Forages in Southeast Asian and Pacific Agriculture. **ACIAR Proceedings**, 12: 96-103.

Treesat, T. (2010). การปลูกอ้อยสูตร 100 ตันต่อไร่ นวัตกรรมใหม่ของโลกทางด้านอ้อย. **Cane Innovation World**. Wangkanai Group, Kanchanaburi, 114p.

Tsai, W.-T., and Tsai, Y.-L. (2016). Thermochemical characterization of napier grass as an energy source and its environmental and economic benefit analysis. **Energy Sources, Part B: Economics, Planning, and Policy**, 11(2): 130-136.

Tscharntke, T., Klein, A.M., Kruess, A., Steffan-Dewenter, I., and Thies, C. (2005). Landscape perspectives on agricultural intensification and biodiversity-ecosystem service management. **Ecology Letters**, 8(8): 857-874.

Tudsri, S., Jorgensen, S.T., Riddach, P., and Pookpakdi, A. (2002). Effect of cutting height and dry season closing date on yield and quality of five Napier grass cultivars in Thailand. **Tropical Grasslands**, 36(4): 248-252.

Unknown. (2015). **Milk for Thai**. Available from http://extension.dld.go.th/th1/images/stories/cattle_buff_bord/napiagrass.pdf, Accessed date: Jan 26, 2015.

Unknown. (2014). **Weeds at SUT**. Nakhon Ratchasima: SUT. Available from http://science.sut.ac.th/gradbio/florae/botanic.html. Accessed date: Nov 21, 2014.

Van de Wouw, M., Hanson, J.H., and Luethi, S. (1999). Morphological and agronomic characterisation of a collection of Napier grass (Pennisetum purpureum) and P. purpureum × P. glaucum. **Tropical Grasslands**, 33(3): 150-158.

Vangnai, S. (1981). Current situation of nodulated legumes in Thailand. Journal of The Science Society Thailand, 7: 18-24.

Veenendaal, E.M., Swaine, M.D., Agyeman, V.K., Blay, D., Abebrese, I.K., and Mullins, C.E. (1996). Differences in plant and soil water relations in and around a forest gap in West Africa during the dry season may influence seedling establishment and survival. **Journal of Ecology**, 84(1): 83-90.

Vermerris, W. (2008). **Genetic Improvement of Bioenergy Crops.** Springer, New York, 450p.

Viator, R.P., Garrison, D.D., Dufrene, E.O., Tew, T.L., and Richard, E.P. (2005). Planting method and timing effects on sugarcane yield. **Crop Management**, 4(1): 1-7.

Vicente-Chandler, J., Silva, S., and Figarella, J. (1959). The effect of nitrogen fertilization and frequency of cutting on the yield and composition of three tropical grasses. **Agronomy Journal**, 51(4): 202-206.

Von Sengbusch, P. (1985). **Einführung in die Allgemeine Biologie**. 3rd ed. Springer, Berlin, 544p.

Wangchuk, K., Rai, K., Nirola, H., Dendup, C., and Mongar, D. (2015). Forage growth, yield and quality responses of Napier hybrid grass cultivars to three cutting intervals in the Himalayan foothills. **Tropical Grasslands-Forrajes Tropicales**, 3(3): 142-150.

Wanjala, B.W., Obonyo, M., Wachira, F.N., Muchugi, A., Mulaa, M., Harvey, J., and Hanson, J. (2013). Genetic diversity in Napier grass (Pennisetum purpureum) cultivars: implications for breeding and conservation. **AoB Plants**, 5(0): plt022.

Waramit, N., and Chaugool, J. (2014). Napier grass: A novel energy crop development and the current status in Thailand. **Journal of ISSAAS (International Society for Southeast Asian Agricultural Sciences)**, 20(1): 139-150.

White, T.J., Bruns, T., Lee, S., and Taylor, J.W. (1990). Amplification and direct sequencing of fungal ribosomal RNA genes for phylogenetics. **PCR Protocols: A Guide to Methods and Applications,** 18(1): 315-322.

Wijitphan, S., Lorwilai, P., and Arkaseang, C. (2009a). Effect of cutting heights on productivity and quality of King Napier grass (Pennisetum purpureum cv. King Grass) under irrigation. **Pakistan Journal of Nutrition**, 8(8): 1244-1250.

Wijitphan, S., Lorwilai, P., and Arkaseang, C. (2009b). Effects of plant spacing on yields and nutritive values of Napier grass (Pennisetum purpureum Schum.) under intensive management of nitrogen fertilizer and irrigation. **Pakistan Journal of Nutrition**, 8(8): 1240-1243.

Williams, C.N. (1980). Fertilizer response of Napier grass under different soil conditions in Brunei. **Experimental Agriculture**, 16(4): 415-423.

Wilsie, C., and Takahashi, M. (1934). **Napier grass (Pennisetum purpureum): A pasture and green fodder crop for Hawaii**. US Government Printing Office, Washington, 26p.

Woodard, K.R., and Prine, G.M. (1990). Propagation quality of elephantgrass stems as affected by the fertilization rate used on nursery plants. **Proceedings-Soil and Crop Science Society of Florida**, 49: 173-176.

Zahid, M.S., Haqqani, A.M., Mufti, M.U., and Shafeeq, S. (2002). Optimization of N and P fertilizer for higher fodder yield and quality in Mottgrass under irrigation-cum rainfed conditions of Pakistan. **Asian Journal of Plant Sciences**, 1(6): 690-693.

Zewdu, T. (2008). Effect of plant density on morphological characteristics, yield and chemical composition of Napier grass (Pennisetum purpureum (L.) Schumach). **East African Journal of Sciences**, 2(1): 55-61.

Zhang, Z., Schwartz, S., Wagner, L., and Miller, W. (2000). A greedy algorithm for aligning DNA sequences. **Journal of Computational Biology**, 7(1-2): 203-214.

# BIOGRAPHY

Mr. Till Haegele was born on July 24, 1975 in Darmstadt, Germany. In 1995, he began studying for his Diploma Engineer (Dipl.-Ing.) in Horticulture, University of Applied Sciences Weihenstephan, Germany. In 2011, he began studying for his Doctor of Philosophy degree at School of Agricultural Engineering, Suranaree University of Technology, Nakhon Ratchasima Province.