The interactions between biotic and abiotic factors that influence the sustainability of tomato production in South Africa

by

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DECLARATION

I hereby certify that this thesis is my own work, except where duly acknowledged. I also certify that no plagiarism was committed in writing this thesis.

Signed: ______________________

Stephanus Malherbe

"We like things nice and simple. Good and evil. Heroes and villains. Most of the time, they're not who we think they are."

James Bradley (Author)

Flags of Our Fathers

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LIST OF ABBREVIATIONS

% bs	percentage (base saturation basis)
% p	percentage of the population
% tg	percentage of the trophic group
A	amoebae
a.i.	active ingredient
AB	active bacteria
AC	active carbon
ADE-4	statistical software package
AF	active fungi
AMC	available moisture content
AN	available nitrogen
ANOVA	analysis of variance
BCA	biological control agent
BER	blossom end rot
BF	bacterial feeding (bacterivorus) nematodes
BI	basal index
BLA	boundary line analysis
C	carbon
CART	classification and regression tree
CEC	cation exchange capacity
CI	channel index
Cil	ciliates
Coeff	coefficient
conv	conventional
c-p	colonizer-persister
CU	cold units

Delta (Δ) T	the difference between the maximum and minimum temperature
DWAF	Department of Water Affairs and Forestry
EC	electrical conductivity
EI	enrichment index
EIQ	environmental impact quotient
Elaph (#)	*Elaphonema* species counts expressed as the numbers per 250 cm^3 of soil
EM	Effective Microorganisms®
ENSO	El Niño southern oscillation
EOM	exogenous organic matter
EOMAN	available nitrogen content of exogenous organic matter
ET	cumulative evaporative demand over a 25-week production period
F	flagellates
FF	fungal feeding (fungivorus) nematodes
FITC	fluorescein isothiocyanate
FLN	free-living nematode
FPE	fermented plant extract
GDD	growing degree days
HD	hyphal diameter
Helico (#, %tg)	*Helicotylenchus* species counts expressed as the numbers per 250 cm^3 of soil (#) or the percentage of the trophic group (%tg)
HQ	high quality
HQY	high quality yield
HSD	honestly significant difference
HU	heat units
IAN	inorganic available nitrogen
IFOAM	International Federation of Organic Agriculture Movements
int	integrated

IPM	integrated pest management
LAI	leaf area index
LSL	long shelf life
MAFD	mean annual frost days
MANOVA	multivariate analysis of variance
MAP	mean annual precipitation
MAPE	mean annual potential evaporation
MAT	mean annual temperature
MI 1-5	maturity index (based on colonizer-persister classes 1-5)
MI 2-5	maturity index (based on colonizer-persister classes 2-5)
MI	maturity index
MPN	most probable number
N	nitrogen
na	not available/not applicable
NCP	nematode community profiling
nd	not determined
ns	not significant
NUE	nitrogen use efficiency
OAN	organic available nitrogen
org	organic
P0	5-week tomato growth stage specific phase: before planting
P1	5-week tomato growth stage specific phase: seedling establishment
P2	5-week tomato growth stage specific phase: initial flowering and fruit set
P3	5-week tomato growth stage specific phase: first harvest period
P4	5-week tomato growth stage specific phase: second harvest period
P5	5-week tomato growth stage specific phase: final harvest period

PAR	photosynthetically active radiation
Paratrich (#, %p, %tg)	*Paratrichodorus* species counts expressed as the numbers per 250 cm^3 of soil (#), the percentage of the total population (%p) or of the trophic group (%tg)
PAST	Paleontological Statistics (software package)
PC	principal component
PCA	principal component analysis
PMN	potentially mineralizable nitrogen
PPI	plant-parasitic index
PPN	plant-parasitic nematode
PW	planting week
SADC	Southern Africa Development Corporation
SAN	available nitrogen in the soil
SAS	soil aggregate stability
SEM	standard error of the mean
SFISA	Soil Foodweb Institute of South Africa
SI	structure index
SOM	soil organic matter
spp.	species
T0	time zero (result at the start of the incubation)
T7	time 7 (result after 7 days of the incubation)
TAN	total available nitrogen
TB	total bacteria
T_{base}	base temperature
TEOMN	total exogenous organic matter nitrogen
TF	total fungi
T_{max}	maximum temperature
T_{min}	minimum temperature

TN	total nitrogen
$TN_{compost}$	total nitrogen content of compost
$TN_{crop\ residues}$	total nitrogen content of crop residues
TN_{manure}	total nitrogen content of manure
TN_{soil}	total nitrogen content of soil
T_{opt}	optimum temperature
TY	total yield
WAP	weeks after planting
WHC	water holding capacity
ZZ2	Brand name of the commercial tomato producer based in the Limpopo Province of South Africa

ABSTRACT

Tomato production was an important economic activity in the Limpopo Province of South Africa. A clear tomato yield gap existed between South Africa and the other countries in Southern Africa. Understanding the reasons behind tomato crop failures and successes in South Africa could increase tomato production in the fast-growing tomato markets of Angola, Mozambique and Zimbabwe, thereby improving food and nutrition security for smallholders and the population in general. In this study, the i) economics of tomato production in South Africa was investigated and compared to similar production systems in the USA, Turkey and India, ii) the interactions between biotic and abiotic factors that limited tomato yield and quality within three climatically distinct planting windows in the Limpopo Province of South Africa were examined, and iii) the correlations between three commercially available soil health metrics (i.e., a microscope-based method for estimating the biomass of soil bacteria, fungi and protozoans; nematode community profiling based on counts and trophic group classifications and related indices; polyphasic soil health testing based on soil biological, physical and chemical variables) and tomato yield were assessed. Meta-analysis was used to explore yield variation in open field production systems in the international context. The main yield-limiting factors were identified as planting times, planting density, soil-water relations, and synthetic/organic nitrogen fertilization. The focus of the study shifted to commercial tomato production in the Limpopo Province of South Africa. Since 2003, these tomato producers practiced intensive open field tomato production using a combination of synthetic and organic soil, crop and pest management technologies. A review of tomato production economics revealed that within a period of six years, South African tomato production cost per hectare more than doubled but the profit margin halved. The importance of tomato quality as an economic factor was demonstrated. Economic pressures forced these tomato producers to intensify production, which underscored the need for the continued development of sustainable tomato production systems. To achieve this strategic goal, the primary biotic and abiotic factors that limited tomato production were identified. The results indicated that complex interactions between biotic and abiotic factors explained yield and quality variation. Climate variation dominated crop productivity, especially in unsuitable planting windows. Soil and crop management variables, notably synthetic fertilizer and pesticide usage, ensured high quality yield. Soil biology management was an important aspect of sustainable agriculture and the use of appropriate soil biology metrics facilitated soil biology management at field scale. All three soil biology metrics were sensitive to distinguish between three types of disturbed soils commonly encountered in the open field tomato production context: natural, disturbed and cultivated soils. The microscope-based method used for quantifying bacterial, fungal and protozoan biomass and numbers was unsuitable for explaining yield variation. Nematode community profiling, in conjunction with polyphasic soil health testing, was very useful for explaining yield variation. In particular, soil pH, boron, aggregate stability, *Paratrichodorus* spp. and the balance among soil cations (especially exchangeable K and Mg) explained yield variation. In conclusion, sustainable open field tomato production depends on the integrated use of synthetic and organic crop nutrition and protection technologies, optimum planting times, disease-resistant genetic material, and cultivation on healthy soils. The findings of this study will benefit policy development in support of sustainable vegetable production in the rural areas of Southern Africa.

Keywords: Climate variation, Economics, Fertilizer, Nematode community profiling, Planting times, Pesticides, Potassium, Soil health

INTRODUCTION

In order to adequately feed the growing global population, research efforts focus on identifying and closing the yield gap for several important crops. Yield gap is defined as the difference between potential yield and the actual yield that realized in the fields (Van Ittersum et al. 2013, Van Wart et al. 2013ab). Yield gap management is an important step towards regional, national and global food security (Shen et al. 2013a, Smith 2013, Van Ittersum et al. 2013, Pasuquin et al. 2014, Sinclair et al. 2014).

The tomato is an important vegetable with a range of reported nutritional and health benefits (Dorais et al. 2008). A tomato yield gap exists in many parts of the world (Asare-Bediako et al. 2007, Barman 2007). A cursory review of the FAOSTAT database confirmed the tomato yield gap that existed between South African and other Southern Africa Development Corporation (SADC) tomato growers: South African tomato growers achieved an average yield of 72.4 t ha^{-1} in 2013 against 2.7-13.0 t ha^{-1} for the other SADC countries (FAOSTAT 2015). Understanding the reasons behind tomato crop failures and successes in South Africa could boost tomato production in the fast-growing tomato markets of Angola, Mozambique and Zimbabwe, thereby improving food and nutrition security for smallholders and the population in general. The focus of this study was to identify biotic and abiotic factors and the role played by each in sustainable tomato production in South Africa

Tomato yield and quality is a function of several possible variables: climate, soil, cultivar, management, pest and disease control, plant nutrition, and irrigation. The interactions between these variables are likely to be complex, making it difficult to inform tomato producers on best management practices for sustainable tomato production in Southern Africa. The tomato is a popular experimental crop and literature contains many references to these likely yield-influencing variables. However, there is a need for identifying and ranking the megatrends that influence tomato production in the multidisciplinary context. Meta-analyses are effective tools for exploring complex questions that are difficult to answer by means of traditional experimentation (Doré et al. 2011, Maillard and Angers 2013, Slattery et al. 2013, Van Kessel et al. 2013, Ugarte et al. 2014).

Despite the relevance of the abiotic megatrends that affect tomato production, the issue of soil health and soil biological testing gained popularity among growers in recent years. Indeed, the promotion of soil health in general, and biological nutrient cycling and biological disease suppression in particular, were identified by many authors as important characteristics of sustainable agriculture (Stirzaker et al. 1989, Becker and Johnson 2001, Altieri 2002, Bergström et al. 2005, Birkhofer et al. 2008, Pretty 2008, Govaerts et al. 2009, Francis and Porter 2011, Gomiero et al. 2011, Lu et al. 2012, Tittonell and Giller 2013, Migliorini et al. 2014). A host of soil health metrics were used in several studies to compare the impact of conventional and organic production systems for several crops. However, very few of these studies, apart from those focusing on plant diseases, correlated soil health results with tomato yield (Ferris et al. 2004, DuPont et al. 2009).

Many of the advanced soil biology related metrics reported in literature are not suitable for routine testing, especially in resource-limited laboratories. However, the value of these tests becomes apparent after a large database of soil biology parameters was constructed and analyzed statistically. Unfortunately, this process is costly because it requires research-grade facilities, a large number of assays, and suitably qualified/experienced personnel. Furthermore, growers may not keep accurate records regarding crop management and site-specific information. Fortunately, the dominant commercial tomato producer in the Limpopo Province, ZZ2, is unique in this regard. At 160,000 tonnes of tomatoes produced annually, the company dominated the local tomato industry with its 32% market share in 2011 (FAOSTAT 2015). In 2002, ZZ2 adopted a nature-friendly tomato farming philosophy which aimed to reduce the ecological impact of farming activities (Taurayi 2011, Uphoff and Thies 2011). Intensive monitoring of the soil biological component of cultivated soils formed the basis of this approach. This thesis is unique because important aspects of the philosophy and long-term practice of ‘ZZ2 Natuurboerdery’ will be evaluated statistically for the first time.

The following objectives were set for this thesis:

1. The first objective of this research project was to evaluate the economics of tomato production in South Africa and to compare that with tomato production in the United States of America, Turkey, and India (Chapter 2).

We hypothesized that production costs are higher and that profitability of tomato production under South African economic conditions are lower as compared to other tomato production regions in the world. We seek to understand why South African tomato growers pursue high yields per hectare while tomato growers in other regions of the world remain profitable with lower yield targets. If the hypothesis is confirmed, it means that intensive tomato cultivation in South Africa is unavoidable, and likely to escalate, due to economic constraints, thereby emphasizing the need for an environmentally sustainable tomato production system. This objective was addressed by means of a literature review and meta-analysis of the relevant literature. Production costs and yield data from a large-scale tomato producer were used for comparison.

2. The second objective focussed on the interaction between biotic and abiotic factors that limit tomato yield in the Lowveld bioregion of the Limpopo Province (Chapters 3 and 4).

We hypothesized that climate effects and more its effect on planting date, had a greater influence on tomato yield per plant than the use of organic and conventional crop management technologies. The impact of these crop management technologies on tomato yield in optimum and sub-optimum climate/soil conditions remain unknown to date, and therefore it was addressed in this study. Detailed tomato yield, climate, and crop and soil management datasets were obtained from a large-scale tomato producer for the period 2003-2010. The datasets were analysed by means of various multivariate statistical procedures.

3. The final objective involved the assessment of the correlation between three commercially available soil biology / soil health metrics and tomato yield in the study area (Chapters 5-7).

We hypothesized that there was a positive correlation between all three soil biology metrics and tomato yield. Three commercially available soil biological metrics were evaluated by these South African tomato producers over an 8-year period: a commercial microscope-based metric which focussed on total and active fungi and bacteria, as well as soil protozoan functional groups (Ingham and Klein 1982, Ingham et al. 1985, 1986), free-living and plant-parasitic nematode community profiling (Yeates et al. 1993, Bongers and Ferris 1999, Ferris et al. 2001), and a composite indicator soil health scoring system (Gugino et al. 2009). The correlations between these metrics and tomato yield were determined by means of uni- and multivariate statistical analyses.

Note to reader: Due to the multidisciplinary character of this research project, a large number of literature is cited in this thesis. A consolidated reference list appears at the end of this thesis to reduce the burden on the reader.

CHAPTER 1

LITERATURE REVIEW

1.1 Introduction

Global demand for food is increasing as a result of the growing global population. Increased agricultural productivity due to advances in agrochemical, genetic, transportation, food preservation, and information management technology characterized the post-World War Two history of modern agriculture (Tilman et al. 2002). However, the resulting escalation in human population growth place ever-increasing demands on the human habitat. Agriculture in particular has had to supply food to more people from arable land and fresh water stocks which rapidly declined in quantity and quality over the last six decades (Ringler and Zhu 2015, Hertel and Baldos 2016). The spectre of climate change adds to the burden of our basic food supply needs (Dube et al. 2016).

A conclusive definition of sustainability is elusive. An analysis of over 100 definitions for the term ‘sustainability’ revealed the complexity and interconnectedness of the concept (White 2013) – the top 10 phrases in the definitions were (ranked from high to low occurrence): *environment, social, economic, life, system, nature, resources, human, development*, and *needs*. Thus, according to White (2013), sustainability implies that environmental, economic and social concerns are in balance. The concept of sustainable agriculture has different meanings and implications for different stakeholders. In the broad philosophical context, the work of Hill (1991, 1998) highlighted the importance of systems-thinking before moving to design and implementation of new technologies. The foundation of Hill’s assertions was the philosophical idea that humans were inseparable from their habitat. From this position, Hill advocated ecological farming as an alternative food production system. Hill advocated energetic pursuance of ecological agriculture – called *deep organics* – and cautioned against half-measures and compromise (so-called *shallow organics*).

Other workers and organizations commented on the concept of sustainable agriculture as well. For some, sustainable agriculture related to the agroecological aspects only, focussing on nutrient cycling, biodiversity and complexity (Altieri 2002), whereas others included aspects of food safety, profitability and social benefits (Tilman et al. 2002, Bergström et al. 2005, Pretty 2008). Fort et al. (2013) found that consumer’s perception of sustainable agriculture differed from those of academics and policymakers. Bergström et al. (2005) viewed sustainable crop nutrient management as the interaction between social, environmental and economic considerations. Ikerd (1993) added spatial and temporal optimization and integration of farming activities as critical for economic and ecological performance. According to IFOAM (2012), sustainability simply meant not using a resource faster than it could be rejuvenated.

A key feature of agricultural sustainability is the sheer complexity of the issue because of the various components that interact or are interdependent. Sustainability in the broad sense is multivariate; this complicates implementation of farm-level sustainability management systems. Characteristics of agricultural sustainability were highlighted by several authors (Stirzaker et al. 1989, Ikerd 1993, Matson et al. 1997, Becker and Johnson 2001, Altieri 2002, Tilman et al. 2002, Bergström et al. 2005, Birkhofer et al. 2008, Pretty 2008, Govaerts et al. 2009, Francis and Porter 2011, Gomiero et al. 2011, Bindraban and Rabbinge 2012, Connor and Mínguez 2012, IFOAM 2012, Lu et al. 2012, Fort et al. 2013, Pham and Smith 2013, Shen et al. 2013ab, Tittonell and Giller 2013, Lemaire et al. 2014, Migliorini et al. 2014) and can be summarized as follows:

- Conserve and promote biodiversity
- Conserve and promote biological nutrient cycling
- Optimize organic and synthetic nutrient addition
- Minimize application of harmful pesticides
- Conserve and promote soil health/quality
- Conserve and promote greater ecosystem ‘health’
- Conserve and promote biological control of pests/diseases
- Optimize water resource management and use
- Rely on an adaptive management system that promotes innovation and science while retaining beneficial aspects of tradition
- Maintain or increase yield
- Maintain financial sustainability and fair profit
- Maintain and promote social sustainability
- Maintain and promote food safety
- Maintain and improve human nutrition
- Promote integrated animal/plant production systems
- Promote carbon sequestration

Indeed, of all the aspects related to the concept of sustainable agriculture, a compromise between organic or conventional extremes was characteristic of a sustainable system in the medium-term. For example, the combination of traditional organic and conventional nutrient management technologies was reported for several crops (Hussain et al. 1999, Khaliq et al. 2006, Gentile et al. 2008, Pan et al. 2009, Gentile et al. 2013, Tong et al. 2014) including tomatoes (Hadar et al. 1985, Stirzaker et al. 1989, De Luca et al. 2006, Montemurro et al. 2009, Campiglia et al. 2010 and 2011, Masaka et al. 2013, Mohanty et al. 2013). Indeed, the combination of inorganic fertilizers and organic materials is foreseen as the only viable solution for Africa's food security challenges (Vanlauwe and Giller 2006).

Therefore, the sustainable agricultural system of the future should integrate the best aspects of both organic and conventional agriculture, avoiding the worst aspects, but not compromising on yield. This is the essence of the *sustainable intensification* concept. High yielding but highly efficient food production systems are required to provide the bulk of our food in future (Shen et al. 2013b). Such systems would not have the negative aspects associated with either conventional or organic farming systems. Therefore, improved efficiency in all aspects of farming would go a long way to realize sustainable intensification (Shen et al. 2013b, Smith 2013).

Sustainable intensification is possible if the best possible soil is provided for the crop, and nutrient supply is matched with nutrient demand by synthetic and organic means; the benefit was sustained food production with reduced environmental impact (Zhang et al. 2011). It also recognizes that agricultural potential differs between biomes and agroecological zones (Tittonell and Giller 2013); thus the pursuit of yields has to be in line with local yield potential estimations, hence the important extension of the term to *ecofunctional agricultural intensification* (Becker and Johnson 2001, Gomiero et al. 2011).

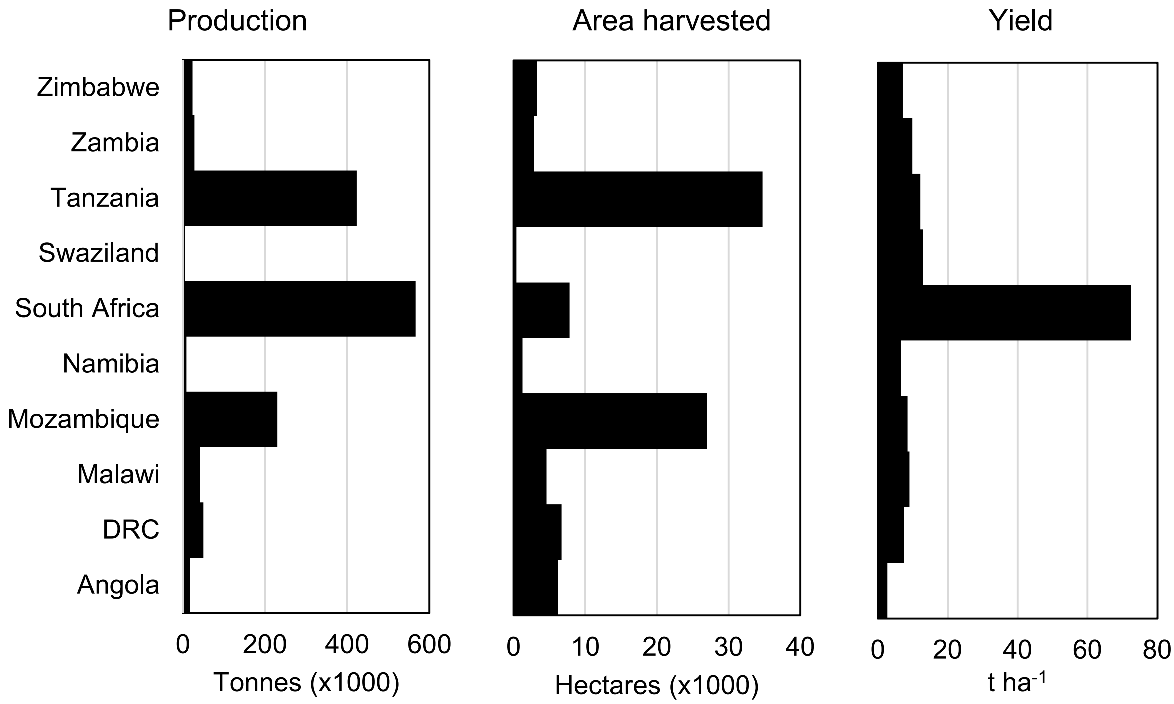
However, risk always lurks in the shadow of opportunity. Sustainable intensification implies getting more from the same patch of soil. Indeed, this could be a step backwards because the negative consequences of monocropping and ecologically unsound farming practices have been documented for decades (e.g., Li et al. 2014a). Thus, the challenge is to implement farming technologies that complies with the basic requirements of agricultural sustainability without compromising yield. The emphasis of ecological intensification is on ecological processes – biological disease control, biological nutrient cycling, and soil health – to reduce the need for agrochemicals (Tittonell and Giller 2013). However, the reliability and extent to which these biological processes leads to measurable and sustained reduction of agrochemical use remains to be demonstrated consistently in the commercial farming context.

Although there is agreement on the objectives or outcomes of sustainable agriculture, the particulars of implementing sustainable crop production are crop- and context-specific (e.g. Poudel et al. 2002, Klaus et al. 2013). For example, the tomato crop has a higher nutrient requirement than most vegetable and field crops (Tei et al. 1998, Elia and Conversa 2012) and it is susceptible to a host of pests and diseases. Therefore, it is difficult to envisage either high-yield organic tomato production or conventional tomato production with no negative ecosystem impact. Due to its culinary popularity and widespread cultivation across the globe, the tomato is a suitable subject for a study into the factors that define the limits of sustainable open field tomato production. A review of fresh market open field tomato production studies was performed in order to identify the agronomic megatrends that govern high- and low-yield scenarios in organic, conventional and integrated open-field, fresh-market tomato production systems.

1.2 Tomato yield gap analysis

To adequately feed the growing global population, research efforts focus on identifying and closing the yield gap for several important crops (Van Ittersum et al. 2013, Van Wart et al. 2013ab). Yield gap is defined as the difference between potential yield and the actual yield observed in the fields. Indeed, optimization of nutrient management, tillage and irrigation saw substantial yield and resource use efficiency increases for important crops such as rice (Liu et al. 2013), maize (Shen et al. 2013ab), and wheat (Peake et al. 2014, Sapkota et al. 2014). Yield gap analysis is a key strategy for increasing on-farm productivity and farmer income (Kamkar et al. 2011). Yield gap management also allows for better use of existing agricultural land (Connor and Mínguez 2012) and is an important step towards regional, national and global food security (Shen et al. 2013ab, Smith 2013, Van Ittersum et al. 2013, Pasuquin et al. 2014, Sinclair et al. 2014).

The tomato is an important vegetable with a range of reported nutritional and health benefits (Dorais et al. 2008). Global tomato production (tonnes) has increased by 27% from 2004 to 2013, with Asia (+60%), Africa (+13%) and Central America (+12%) showing the strongest regional growth, America and Europe contracted (-12% each), and South America (+4%) stabilized (FAOSTAT 2015). At 50.6 million tonnes produced per annum, China was by far the largest tomato producer in the world in 2013. Tomato production in the Southern African Development Corporation (SADC) region demonstrated rapid growth (+80%) over the same 2004-2013 period. Despite ranking 34th in the world based on total tonnage in 2013, South Africa produced 41% of the tomatoes from 8% of the total hectares in the SADC region in 2013 (Fig. 1.1). A substantial tomato yield gap exists within the SADC region, even though several countries have climate conditions suitable for open-field tomato production.



DRC = Democratic Republic of the Congo; the islands of Mauritius and Seychelles were excluded from the analysis.

FIG. 1.1: Summary of tomato production in the SADC region in 2013 (FAOSTAT 2015)

Tomatoes are cultivated in all the provinces of South Africa. Covered cultivation occurs near the major metropolitan areas in Gauteng, KwaZulu-Natal and the Western Cape provinces, but 75% of open field production occurs in the Limpopo Province (DWAF 2011). Understanding the reasons behind tomato crop failures and successes in South Africa could increase tomato production in the fast-growing tomato markets of Angola, Mozambique and Zimbabwe, thereby improving food and nutrition security for smallholders and the population in general.

Crop yield gap is addressed in several ways. The yield gap must first be verified, the mechanisms causing the yield gap identified, and then the production system should be managed until the yield gap is closed. For example, crop yield gap is managed by focussing on the following aspects (Barman 2007, De Ponti et al. 2012, Sinclair and Rufty 2012, Affholder et al. 2013, George 2013, Liu et al. 2013, Shen et al. 2013a, Tittonell and Giller 2013, Pasuquin et al. 2014, Rahman et al. 2014, Sapkota et al. 2014, Sinclair et al. 2014, Xie et al. 2014):

- Cultivar characteristics
- Nutrient management
- Water management
- Pest/disease management
- Weed management
- Plant density
- Planting dates
- Harvest dates
- Crop production best practices
- Technology management
- Production costs

This is a cyclical process of continuous learning and responding as environmental and economic factors fluctuate over time. Bridging the knowledge gap will do a lot to close the yield gap (Ikerd 1993). However, tacit knowledge itself will not close the yield gap, but expert implementation of that knowledge is the real key to closing the tomato yield gap (Barman 2007).

A review of tomato production economics from examples in the USA, Turkey, India and South Africa showed that high-yield high-quality tomato production was the key to economically sustainable tomato production (Stoddard et al. 2007, VanSickle et al. 2009, Keskin et al. 2010, Bhardwaj et al. 2011, Galinato et al. 2012, Sheahan et al. 2012; see Chapter 2). Tomato yield and quality are a function of several possible factors: climate, soil, cultivar, management, pest and disease control, plant nutrition and irrigation. These factors are known to influence tomato yield and can be reviewed in isolation, but tomato yield is influenced by a complex combination of these factors. The tomato is a popular experimental crop and literature contains many references to these likely yield-influencing variables. However, there is a need for identifying and ranking the megatrends that influence tomato production in a multidisciplinary context. Meta-analyses are effective tools for exploring complex questions that are difficult to answer by means of traditional experimentation (Doré et al. 2011, Maillard and Angers 2013, Slattery et al. 2013, Van Kessel et al. 2013, Ugarte et al. 2014). Hence, the focus of this literature review is determined by the results of a meta-analysis on the factors that influence open field tomato production.

1.3 Meta-analysis

A meta-analysis was performed on literature extracted from Science Direct and Google Scholar (Google Inc., Mountain View, CA, USA) with the following keywords: tomato, organic, conventional. Studies featuring deliberate inoculation with disease-causing agents were omitted. Studies using processing tomato cultivars and practices were omitted because crop management objectives differed substantially from dedicated fresh-market tomato production (Table 1.1).

TABLE 1.1: Characteristics of fresh-market and processing tomato production (QG DAF 2014, USDA ERS 2016, Yara 2016)

Variable	Fresh-market tomatoes	Processing tomatoes
Cultivars	Mostly indeterminate	Mostly determinate
Production method	Staked/trellised	In bushes close to the ground
Final product at harvest	Green to light pink (immature)	Red (mature)
Market prices	Typically high	Typically low
Growing season	Medium to long (90-175 days)	Short (60-90 days)
Harvest method	Hand	Mechanical
Yield	Yield is similar to or lower than processing tomatoes	Yield is similar to or higher than fresh-market tomatoes

Several hundred publications were retrieved and evaluated for completeness in terms of the criteria described in the following sections.

1.3.1 Categorical variables

Production systems were defined as either ‘conventional’ (only used synthetic fertilizers, pesticides and herbicides), ‘organic’ (only used natural nutrient sources and organic pest/disease/weed control methods), or ‘integrated’ (combinations of organic/ conventional technologies were used for crop nutrition or protection). Cultivation years were categorized as ‘dry’ or ‘wet’ if explicitly indicated as such by authors and precipitation data deviated substantially from long-term averages; 'normal' implied no deviance from long-term average for the specific tomato production region and not indicated as abnormal by authors. Where soil textures were not explicitly given, or only soil series were described, soil texture information was inferred from the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC 2012) based on the experimental site's location or from other literature sources that described the soil series in more detail. Soil texture data was then categorized in three classes according to FAO/IIASA/ISRIC/ISS-CAS/JRC (2012): 'coarse-textured' (<18% clay but >65% sand), 'medium-textured' (<35% clay and <65% sand), and 'fine-textured' (>35% clay).

1.3.2 Inferred variables

The following variables were calculated:

$$\text{Season duration (Weeks)} = \text{harvest date} - \text{planting date} \tag{1.1}$$

$$\text{Yield (t ha}^{-1}) = \text{marketable yield or (total yield x 0.7, Stoddard at el. 2007)} \tag{1.2}$$

$$\text{Yield plant}^{-1} \text{ (kg plant}^{-1}) = \text{marketable yield ha}^{-1} / \text{planting density ha}^{-1} \tag{1.3}$$

Tomato production is highly dependent on N nutrition and excessive N fertilization is associated with greater risk of leaching (thus less environmentally sustainable), hence the focus on this issue in this meta-analysis. All N-related data were calculated on a kg N ha^{-1} basis. The total nitrogen (TN) content of soils (TN_{soil}, kg N ha^{-1}) was calculated from total N (as %) assuming soil depth of 15 cm and bulk density of 1.2 g cm^{-3}. Where TN_{soil} was not given, it was calculated from the soil organic matter (SOM) content assuming 5% N content for SOM (Schulten and Schnitzer 1998). Various organic N sources were encountered in literature. The total exogenous organic matter nitrogen (TEOMN) variable accounts for the total N supplied by manures, composts, or cover crop residues:

$$\text{TEOMN} = \text{TN}_{\text{manure}} + \text{TN}_{\text{compost}} + \text{TN}_{\text{crop residues}} \tag{1.4}$$

The available nitrogen (AN) content of the exogenous organic matter (EOM) was calculated assuming 30% availability (Fu et al. 1987, Bulluck et al. 2002b, Curless and Kelling 2003, Garnier et al. 2003, Cordovil et al. 2005):

$$\text{EOMAN} = \text{TEOMN x } 30\% \tag{1.5}$$

The soil available nitrogen (SAN) content was calculated assuming a conservative 2% availability (Cassman et al. 2002):

$$SAN = TN_{soil} \text{ x } 2\% \tag{1.6}$$

The organic available nitrogen (OAN) variable accounted for nitrogen released from the soil organic matter fraction as well as the EOM:

$$OAN = SAN + EOMAN \tag{1.7}$$

The total available nitrogen (TAN) variable accounted for all organic and inorganic available N (IAN; synthetic fertilizer N was assumed to be 100% available for plant uptake):

$$TAN = OAN + IAN \tag{1.8}$$

The IAN, OAN, and TAN values were expressed on a kg N plant^{-1} and kg N tonne^{-1} tomato basis. Finally, the contribution of the inorganic fertilizer component to the total N available for crop uptake was calculated as the ratio of IAN/TAN (but expressed as %).

$$IAN/TAN = (IAN / TAN) \text{ x } 100 \tag{1.9}$$

1.3.3 Dataset and analyses

The final dataset contained 322 entries from 31 publications covering medium fruit size cultivars, fresh-market, and open-field tomato production (Table 1.2). Descriptive statistics of the dataset is given in Table 1.4. The dataset was subjected to Classification and Regression Tree (CART) analysis using R (*ctree* package; http://www.r-project.org/). CART analysis is widely used in the field of medicine and have recently been used in many situations in applied agricultural research (Shepherd et al. 2003, Speybroeck et al. 2004, Orr et al. 2007, Smukler et al. 2008, Tittonell et al. 2008, Ferraro et al. 2009, Zheng et al. 2009, Zhang et al. 2012). An important advantage of CART is the ability to analyse continuous and categorical entries simultaneously. Univariate statistics were done using PAST 2.17b (Hammer et al. 2001).

TABLE 1.2: Description of studies used in the meta-analysis

		Number of treatments		
References	**Country**	**Conv[1]**	**Int[1]**	**Org[1]**
Abdul-Baki et al. (1992)	USA Mid-Atlantic	8		
Abdul-Baki et al. (1996)	USA Mid-Atlantic	5		3
Abdul-Baki et al. (1997)	USA Mid-Atlantic	16	16	
Aldrich et al. (2010)	USA Southwest	9		9
Arancon et al. (2003)	USA Midwest	1	6	
Bhattarai et al. (2006)	Australia	4		
Briar et al. (2011)	USA Midwest			6
Buyer et al. (2010)	USA Mid-Atlantic	9	18	
Carrera et al. (2007)	USA Southeast	2	13	
Çetin and Uygan (2008)	Turkey	6		
Cushman and Snyder (2002)	USA Florida	4	6	
Firoz et al. (2009)	Bangladesh	3		
Guertal and Kemble (1998)	USA Southeast	10		
Hebbar et al. (2004)	India	8		
Huang and Snapp (2004)	USA Great Lakes	12		
Ilíc et al. (2012)	Serbia		1	
Locascio et al. (1996)	USA Florida	5		
Locascio et al. (1997)	USA Florida	6		
Malash et al. (2005)	Egypt	4		
Maršic et al. (2005)	Slovenia	12		
Masaka et al. (2013)	Zimbabwe		12	
Nault and Speese (2002)	USA Southeast	6		
Ngouajio et al. (2007)	USA Great Lakes	12		
Sainju et al. (2000)	USA Southeast		12	
Sainju et al. (2001)	USA Southeast	4		8
Scholberg et al. (2000)	USA Florida	4		
Stoffella and Graetz (2000)	USA Florida	2	2	2
Teasdale and Abdul-Baki (1998)	USA Mid-Atlantic		30	
Warman (2005)	USA Northeast	1		1
Zaller (2006)	Germany			6
Zotarelli et al. (2009)	USA Florida	18		
	Subtotal	**171**	**116**	**35**

[1] Production systems: conventional (conv), integrated (int), organic (org) – see text for definitions

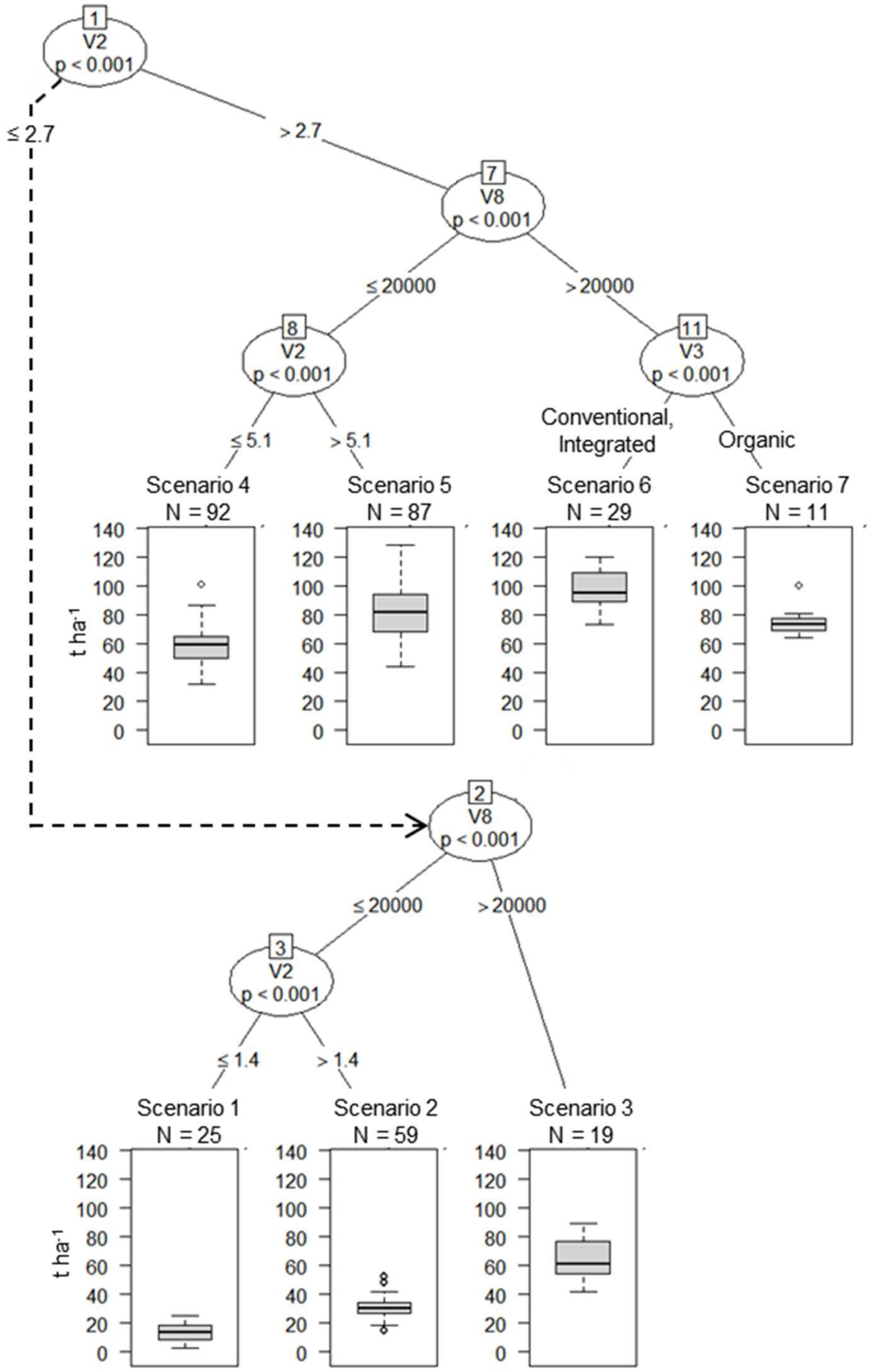
TABLE 1.3: Descriptive statistics for the meta-analysis dataset

Continuous variables[a]	**Units**	**Min**	**25th per-centile**	**Mean**	**Median**	**75th per-centile**	**Max**
Yield	t ha^{-1}	2.2	36.2	60.2	59.9	81.4	128.2
Yield	kg plant^{-1}	0.3	2.4	3.9	3.8	5.4	10
Season	Weeks	11.9	14.3	15.9	15.0	18.3	23.4
Density	plants ha^{-1}	7689	13300	16489	13888	20000	35500
IAN	kg N ha^{-1}	0.0	90.0	147.5	130.0	196.0	560.0
EOMAN	kg N ha^{-1}	0.0	0.0	64.4	0.0	41.7	1496.1
OAN	kg N ha^{-1}	9.0	16.2	89.5	38.7	62.4	1535.7
SAN	kg N ha^{-1}	3.6	15.5	25.1	19.8	39.6	75.6
TAN	kg N ha^{-1}	9.0	141.9	236.9	190.1	234.8	1535.7
TEOMN	kg N ha^{-1}	0.0	0.0	214.6	0.0	139.0	4987.0
TN$_{soil}$	kg N ha^{-1}	180.0	774.0	1254.1	990.0	1980.0	3780.0
EOMAN	g N plant^{-1}	0.0	0.0	5.6	0.0	3.0	134.8
IAN	g N plant^{-1}	0.0	5.1	10.0	8.1	12.6	69.5
OAN	g N plant^{-1}	0.4	1.1	7.4	2.45	4.8	138.4
SAN	g N plant^{-1}	0.1	1.1	1.8	1.2	2.9	9.1
TAN	g N plant^{-1}	1.2	8.7	17.5	12.2	16.1	144.3
TEOMN	g N plant^{-1}	0.0	0.0	18.6	0.0	10.0	449.3
TN$_{soil}$	g N plant^{-1}	6.9	52.9	89.8	58.4	142.6	453.8
IAN:TAN	%	0.0	52.5	65.5	75.5	91.8	97.6

[a.] Density: planting density; EOMAN: exogenous organic matter available N; IAN: inorganic available N; IAN:TAN: ratio of IAN to TAN; OAN: organic available N; SAN: soil available N; TAN: total available N; TEOMN: total exogenous organic matter N; TN$_{soil}$: total N content of soil

1.4 Results and Discussion

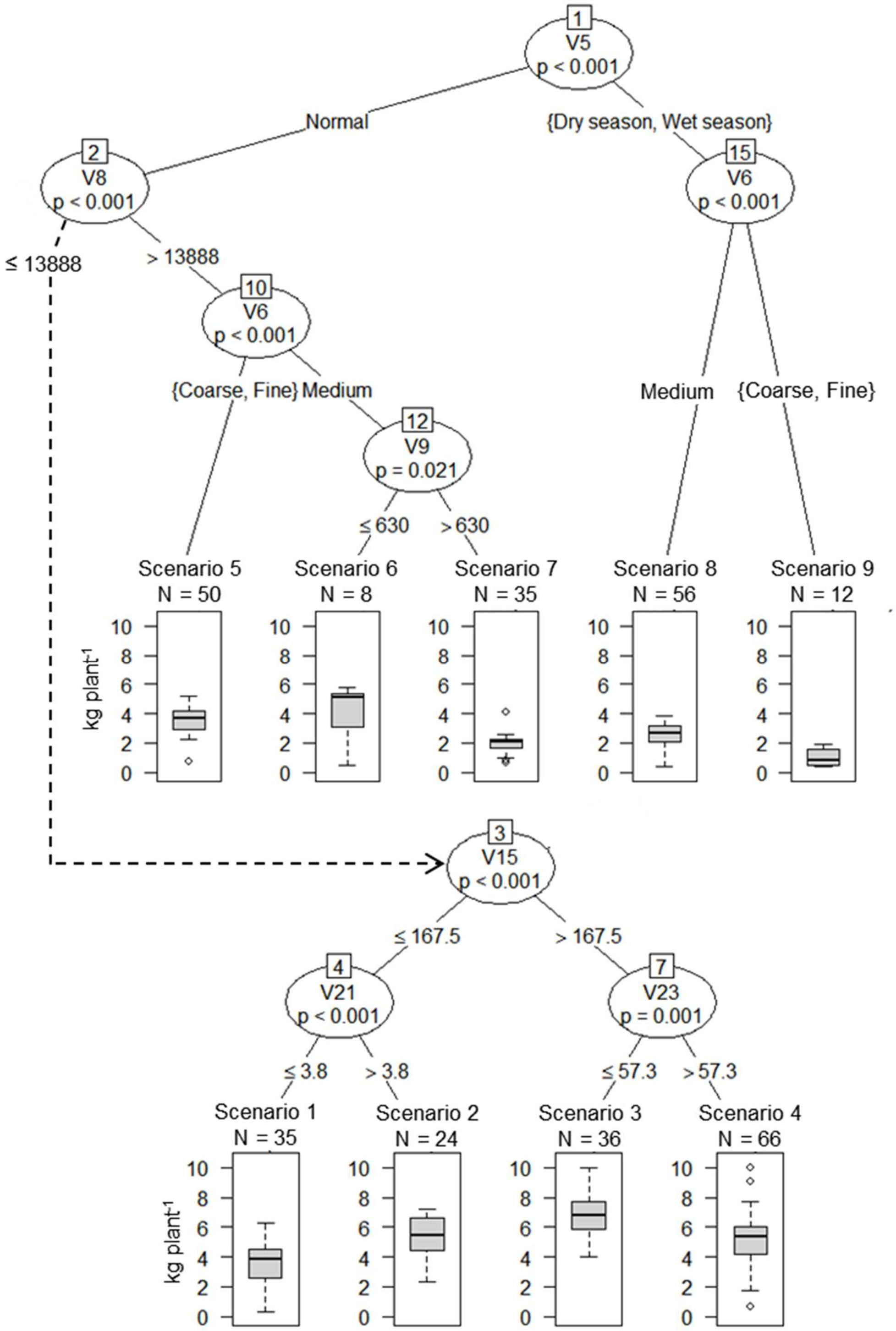
The initial CART analysis results indicated that yield per hectare was dominated by interactions between planting density (plants ha^{-1}) and yield per plant (kg plant^{-1}) (Fig. 1.2). The interaction between yield per hectare and yield per plant follows the logical assumption that yield per plant directs yield per hectare. Therefore, successful open field tomato production depends on the right combination of factors that govern yield per plant and planting density.



Key: V2 (yield, kg plant^{-1}), V3 (production system), V8 (planting density, plants ha^{-1}), N = number of entries per scenario

FIG. 1.2: Interactions between tomato yield and planting density as depicted by CART analysis

Subsequent CART analysis, using yield per plant as outcome variable, indicated that a complex set of interactions influence tomato yield (Fig. 1.3). These results will form the basis of this literature review and will be discussed in more detail in the following sections.

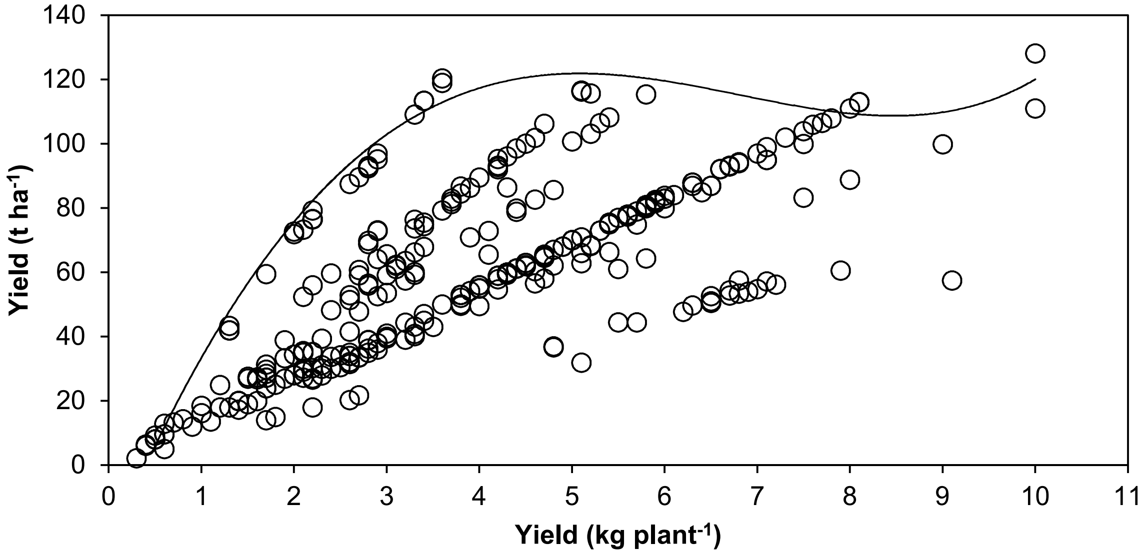


Key: V5 (Precipitation), V6 (Soil texture), V8 (Planting density), V9 (Total N in soil, kg N ha^{-1}), V15 (Total available N, kg N ha^{-1}), V21 (Organic available N, g N plant^{-1}), V23 (IAN:TAN, %), N = number of entries per scenario

FIG. 1.3: Variables that influence yield per plant as depicted by CART analysis

1.4.1 Yield and planting density

The marketable yields reported in this meta-analysis ranged from 2.2 to 128.2 t ha^{-1} with a mean and median of 60.2 and 59.9 t ha^{-1} respectively (Table 1.3). This was in agreement with yields reported for similar tomato production systems in Turkey (74 t ha^{-1}, Engindeniz 2006, 2007), California (87.9-146.t t ha^{-1}, Hanson and May 2006) and South Africa (72.4 t ha^{-1}, FAOSTAT 2015). Boundary line analysis indicated that the maximum attainable yield for open field conditions to be around 120-130 t ha^{-1} (Fig. 1.4).



Note: Boundary line represents 4th degree polynomial

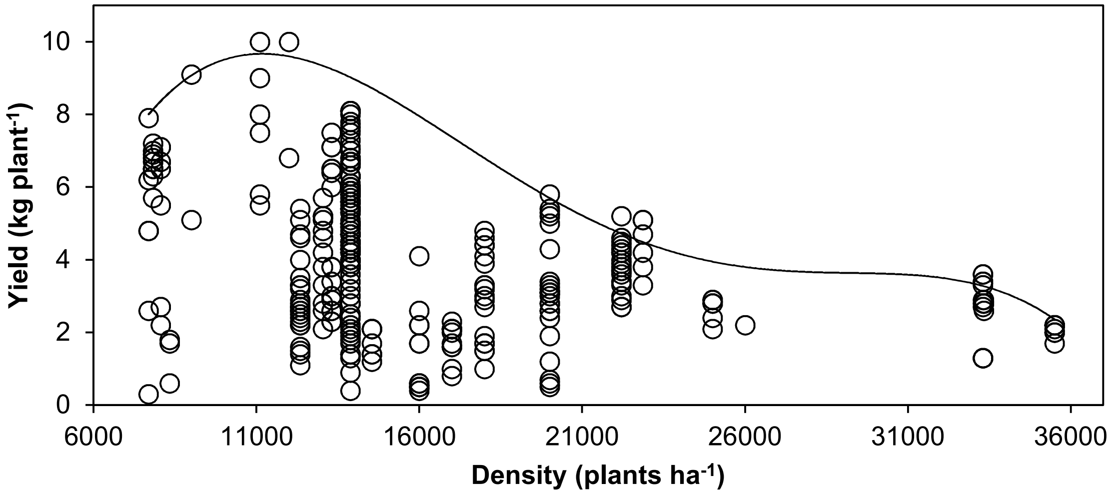
FIG. 1.4: Relationship between yield per plant and yield per hectare

Covered cultivation systems recorded higher fresh-market tomato yields which ranged from 144 t ha^{-1} in Turkey (Canakci and Akinci 2006) to more than 300 t ha^{-1} in Denmark and the Netherlands (Sorensen and Thorup-Kristensen 2006, Thybo et al. 2006, Verheul et al. 2012). The difference between yields of open-field and protected cultivation systems underscores the dominant influence of climate and associated pests/diseases on marketable tomato yield.

Planting density refers to the number of plants cultivated per hectare and is determined by within- and inter-row spacing. Planting density can be adjusted if seedlings are pruned to develop two or more main branches per seedling, thus increasing the number of fruit-bearing stems per hectare (Marcelis et al. 2009).

The interaction between planting density and tomato yield is directly related to prevailing light intensity. Higher photosynthetically active radiation (PAR) level allows for high planting densities (Marcelis et al. 2009, Verheul et al. 2012), but the correlation is bimodal (i.e., crop growth rate is lower at the lower or higher extremes of the PAR spectrum; Heuvelink 1995, Fan et al. 2013). Nitrogen nutrition increases the leaf area index (LAI) and thus the absorption of PAR (Tei et al. 2002), which in turn allows the plant to develop and grow better due to the availability of photosynthate, the building blocks of the plant (Ho 1996). Cumulative intercepted radiation is also correlated with tomato fruit weight (Scholberg et al. 2000). However, excessive PAR limits photosynthetic processes (Matsuda et al. 2012, O'Carrigan et al. 2014). In countries where irradiance level is reduced during the winter months, continuous lighting in the greenhouse environment has proven to be advantageous (Velez-Ramirez et al. 2012).

The meta-analysis results indicate that highest yields per hectare are achieved at below-average planting densities, provided the yield per plant is high (Fig. 1.2). However, the yield per plant decreases at very high planting densities (Fig. 1.5).

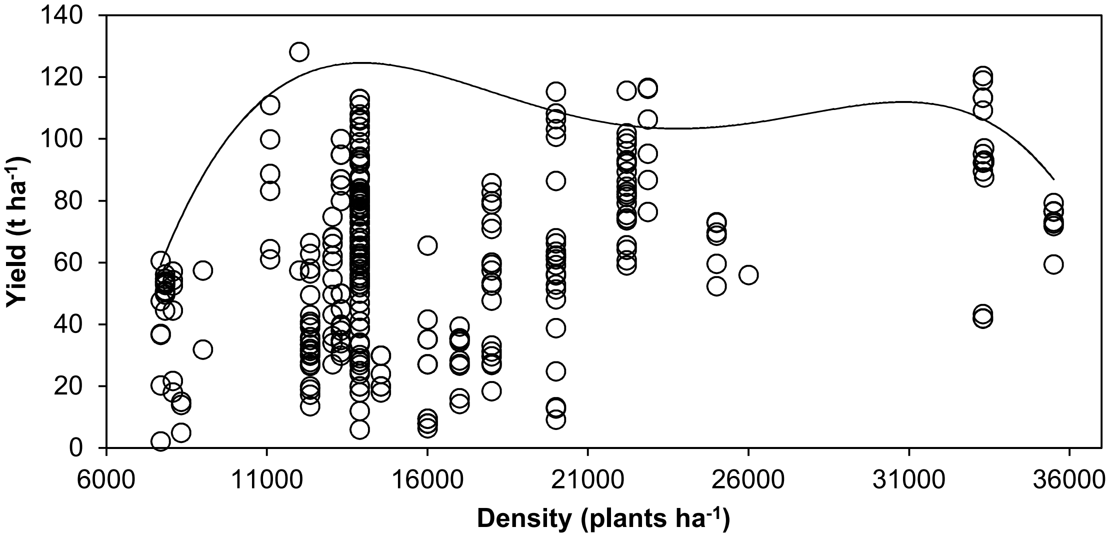


Note: Boundary line represents 4th degree polynomial

FIG. 1.5: Interaction between planting density and tomato yield per plant

In the open field production environment, clouds create local climate conditions with reduced sunlight irradiance, thus reducing primary activity because of less PAR that reaches the plant (Alton 2008); such conditions result in poorly developed plant canopies, reduced plant growth and eventually poor crop yield (Zotarelli et al. 2009). However, irradiance reduction can be a man-made phenomenon as well. High planting densities cause automatic light restriction due to excessive leaf growth and rapid subsequent canopy development. This results in increased fruit number but lower fruit mass, thus lowering the overall yield (Heuvelink 1995, Qiu et al. 2013). If this is not managed through canopy pruning, demand for available PAR outstrips actual PAR availability, leading to reduced crop growth and suboptimal fruit set. An excessively prolific canopy leads to lower yields because of photosynthate utilization competition between actively growing foliage and fruits (Moreno et al. 2003). For this reason, foliage pruning is a key tactic for increasing marketable yield resulting in increased fruit size due to tipping the source/sink balance in favour of fruit growth (Massa et al. 2013).

The results of this meta-analysis show that planting densities optimized in response to prevailing PAR levels is an important approach for increasing tomato yields per hectare. Effective pruning is a key tactic for converting vegetative growth gains into high fruit yield, thereby increasing the yield per plant. In the multivariate context, plant productivity is best at planting densities < 13000 plants ha^{-1} (Fig. 1.3) – provided precipitation and crop nitrogen nutrition are optimal. However, when yield per plant is expected to be low due to unfavourable climatic conditions, reasonable total yields can be achieved at higher planting densities (Fig. 1.6).



Note: Boundary line represents 4th degree polynomial

FIG. 1.6: Interaction between planting density and tomato yield per hectare

1.4.2 Soil-water relations

In this meta-analysis dataset, precipitation is the first variable to split the dataset between low and high yield scenarios (Fig. 1.3). During excessively wet or dry years, low and high yield bifurcates at soil texture as categorical variable (scenarios 8 and 9 in Fig. 1.3). These interactions will be discussed in more detail in the following paragraphs.

Long-term decline in rainfall is projected to influence food security in Africa (Sassi and Cardaci 2013). Although the lack of water severely impacts crop performance, excessive rainfall or over-irrigation is the cause of yield gap for many crops (Kamkar et al. 2011, Braunack et al. 2012, Xie et al. 2014). Vegetable crops are more sensitive to flooding than field crops (Rao and Li 2003). Indeed, irrigation problems cause a range of complications which severely limits tomato production in Africa (Asare-Bediako et al. 2007).

Annual weather variation often confounds research results especially if tomato yield is assessed (Skąpski and Pyzik 1990, Cuartero and Rodriguez 1994, Ngouajio et al. 2007, Favati et al. 2009, Montemurro et al. 2009, Zotarelli et al. 2009, Aldrich et al. 2010, Elia and Conversa 2012, Sydorovych et al. 2013). Annual variation is often substantial and yield variation ranges from 50% to 74.8% between treatments (Creamer et al. 1996, Teasdale and Abdul-Baki 1998, Tourte et al. 2000, Tei et al. 2002, Ngouajio et al. 2007). Annual variation in tomato yield can be attributed to suboptimal growing degree days (GDD) and heat waves (Lacatus et al. 1994), but variation in precipitation is the major factor reported in literature (Tourte et al. 2000, De Pascale et al. 2006, Ngouajio et al. 2007, Favati et al. 2009).

Water supply is a critical component of tomato yield because of its direct influence on fruit size, mass and taste (Bar-Yosef and Sagiv 1982b, Phene et al. 1992, Dadomo 1994, Dumas et al. 1994, Veit-Köhler et al. 1999, Topcu et al. 2007, Wang et al. 2011). Hebbar et al. (2004) reported a 20% increase in tomato yield after optimization of irrigation. Indeed, optimized irrigation and nutrient management enabled tomato cultivation to remain economically viable in Australia despite significant damage to roots caused by plant-parasitic nematodes (Stirling and Smith 1998).

Excessive rainfall or over-irrigation causes waterlogging of roots and tomato roots are particularly sensitive to hypoxia (Shi et al. 2007). Root hypoxia causes the release of ammonium and nitrite into the growth medium, reduces amino acid turnover, and increases susceptibility to nutrient toxicity (Phipps and Cornforth 1970, Summers et al. 2009). The direct result on the root system is a reduction in root biomass and production of adventitious roots around the stem base (Bradford and Hsiao 1982, Vartapetian and Jackson 1997, Dresbøll et al. 2013). Symptoms of flooding are typical of N deficiency symptoms: leaf yellowing and wilting (Bhattarai et al. 2006, Ezin et al. 2010). Plant photosynthesis is negatively affected by flooding due to reduced stomatal conductance and transpiration (Bradford and Hsiao 1982, Karlen et al. 1983, Ezin et al. 2010). Reduction in leaf number and leaf area index after flooding has also been reported (Cavero et al. 1998, Ezin et al. 2010, Zheng et al. 2013). The increased rate of fruit maturation is an important side-effect of flooding (Karlen et al. 1983, Horchani et al. 2008) and is associated with ethylene production (Jackson et al. 1978, Bradford and Hsiao 1982, Hadid et al. 1986, Horchani et al. 2008). This phenomenon has divergent implications for producers: a) early fruit maturing is problematic especially if the fruit size is suboptimal, which means the cumulative yield will be lower than expected, or b) water stress can be used to hasten or delay fruit maturation to exploit short-term market price variation.

The impact of excessive rainfall or over-irrigation depends on when it occurs during the tomato's growth cycle. The ability of the tomato crop to tolerate and recover from excessive rainfall events varies with growth stage. The flowering stage is the most sensitive stage (Lopez and Del Rosario 1983, Hadid et al. 1986, Alvino et al. 1990, Phene et al. 1992, Hanson et al. 2000, Sainju et al. 2000, De Pascale et al. 2006, Zotarelli et al. 2009, Chen et al. 2013), resulting in reduced fruit set and a marked decrease in yield. Short-term flooding experienced during fruit maturation results in reduced marketable yield, higher fruit numbers but poor fruit quality (Karlen et al. 1983, Yrissary et al. 1993, Dadomo 1994, Colla et al. 2000, Sainju et al. 2000, Wang et al. 2011, Chen et al. 2013, Zheng et al. 2013). Apart from growth stage, cultivar differences can also play a role in resilience to water stress (May and Gonzales 1999, Ezin et al. 2010, Mahadeen et al. 2011). Indeterminate varieties flower continuously and are therefore constantly sensitive to water stress (Hanson et al. 2000). Furthermore, flood sensitive cultivars take longer to form flowers and mature (Ezin et al. 2010).

Tomato seedlings are sensitive to excess moisture but less so than mature plants due to the relatively shallow root systems of seedlings compared to the deep root systems of mature tomato plants (Ngouajio et al. 2007). Ngouajio et al. (2007) reported that avoiding excessive irrigation of seedlings increased marketable yield and fruit number by 8-15% and 12-14% respectively, while the overall water requirement was reduced by 20%. However, an initial water-related setback can be surpassed if optimal climate conditions such as low humidity, high temperature, and adequate light intensity prevail during the remainder of the growing season.

Water stress events can cause additional non-rhizosphere problems on a wider scale since high humidity usually accompanies a rainfall event, resulting in the onset of foliar disease (Carrera et al. 2007, Zotarelli et al. 2009). The negative impact of excessive rainfall can last for several months in natural ecosystems (Walter et al. 2012). This has implications for fallow management between tomato cultivation events. For example, Sainju et al. (2000) witnessed how above-average rainfall in the current year negated the benefits of tillage in the preceding dry year. The short-term negative impact of excessive rainfall can be managed by optimizing planting times, improving plot-level drainage through contouring, planting on ridges or raised beds, and reduced leaf pruning (Rao and Li 2003, Bhattarai et al. 2006).

The ability of organic matter to improve soil functioning is widely recognized by farmers and academics. However, the ability of soil organic matter to enhance soil water holding capacity is detrimental to crop performance under specific conditions (Papadopoulos et al. 2014). Excessive levels of organic matter in heavy soils increase crop susceptibility to water stress and can be associated with yield reduction in tomato (El-Beltagy et al. 1986, Argerich et al. 1999, Colla et al. 2000). Soil organic matter improves the moisture holding capacity of soils but when combined with high soil clay content (Gutiérrez-Miceli et al. 2007), in the presence of excess soil moisture, it stimulates anaerobic microbial activity and leads to the accumulation of anaerobic metabolic by-products and ammonium. Root hypoxia and its effects occurs easier in heavy fine-textured soils than well-drained coarse-textured soils (Huett 1989, Bhattarai et al. 2006, Cantore et al. 2012). If not corrected, the end-result is reduced crop growth and lower yield. Ammonium toxicity is unlikely in well-drained soils because of the rapid microbial conversion of ammonium to nitrate (Cavero et al. 1997, Cushman and Snyder 2002, Horchani et al. 2010). Despite these reports, Carrera et al. (2007) reported that tomato plants grown in compost-amended soils demonstrated increased resilience during excessive rainfall events and resulted in 25-56% higher yield than the fertilizer-only control. More research is required into the interactions between soil organic matter management technologies, soil type, irrigation/rainfall and marketable tomato yield.

Regarding the meta-analysis results, soil texture and soil nitrogen content plays a role in explaining yield variation at high planting densities (> 13 888 plants ha^{-1}). The average yield per plant is slightly higher in coarse/fine (3.6 kg plant^{-1}; scenario 5) than medium textured soils

(3.1 kg plant^{-1}; scenarios 6 and 7 combined under node 12; Fig. 1.3). Although the difference in yield per plant between coarse/fine (scenario 5) and poor quality medium textured soils (total soil N ≤ 630 kg N ha^{-1}, scenario 6) is not significant (Kruskal-Wallis $P > 0.10$), the average yield per plant is substantially lower in the relatively fertile soils (1.9 kg plant^{-1}, scenario 7, total soil N > 630 kg N ha^{-1}). Thus, the soil fertility status is an important condition for understanding yield variation in medium but not in fine/coarse textured soils. This observation is surprising, which means the influence of soil organic matter on tomato yield has to be reviewed as well. Therefore, tomato nitrogen nutrition and the contribution of organic N sources will be reviewed in the following sections.

1.4.3 Nitrogen nutrition management

1.4.3.1 Tomato nitrogen requirements

Tomatoes have an above-average nitrogen demand in comparison to other crop types. For example, Huett (1996) reported the maximum N requirement for tomatoes is 66 kg N ha^{-1} week^{-1} whereas for peach this value was 1.3 kg N ha^{-1} week^{-1}, while annual application of 150 kg N ha^{-1} for wheat and maize was reported in China (Xie et al. 2009). In comparison to other vegetable crops, maximum production of leeks and cabbages is achieved with 220 and 320 kg N ha^{-1} (Sorensen 1993). Nitrogen application rate for conventional tomato farms in California range from 78 to 303 kg N ha^{-1} (Letourneau et al. 1996). Elia and Conversa (2012) discovered that although the recommended nitrogen application rate for processing tomato in the Apulia region of Southern Italy is 200 kg N ha^{-1}, local farmers use 350-400 kg N ha^{-1}.

The inorganic N application rates reported for this meta-analysis range from 0 to 560 kg N ha^{-1} with a mean and median of 147.5 and 130.0 kg N ha^{-1} respectively (Table 1.3). The organic available N application rates reported for this meta-analysis range from 9.0 to 1535.7 kg N ha^{-1} with a mean and median of 89.5 and 38.7 kg N ha^{-1} respectively (Table 1.3). The total available N per hectare range from 9.0 to 1535.7 kg N ha^{-1} with a mean and median of 236.9 and 190.1 kg N ha^{-1} respectively. Synthetic and/or organic application rates of 300-560 kg N ha^{-1} reported in literature are therefore on the high-end of the scale (Scholberg et al. 2000, Nault and Speese 2002, Elia and Conversa 2012, Masaka et al. 2013). The recommended N requirements for tomatoes in Florida is 200 kg N ha^{-1}, but exceeds 300 kg N ha^{-1} if certain conditions prevailed (Ozores-Hampton and Simonne 2011). Additional fertilizer should be added only if specific conditions warrant it: N loss due to rain or over-irrigation, low-leaf N content, or extended growth season due to favourable climatic factors (Ozores-Hampton and Simonne 2011). Fertilization, however, does not only play an important role in terms of crop yield, but was also found to improve tomato taste (Cliff et al. 2012).

Tomatoes respond readily to increased N fertilization rates above 100 kg N ha^{-1} (Warner et al. 2004, Parisi et al. 2006). A strong correlation exists between nutrient uptake and tomato dry matter yield (Kirkby and Mengel 1969). Tomato plants require N in the form of either ammonium (NH_4^+) or nitrate (NO_3^-) and is fertilized with either ammonium or nitrate-based fertilizers. Tomato nutrient demand is determined by various methods. An industry rule-of-thumb involves multiplying the target yield by 2.4 (Hanson et al. 2000); for example, a 100 t ha^{-1} yield would require 240 kg N ha^{-1}. Similar values are reported by other researchers: 2.24 (Tei et al. 2002), 2.35 (Bar-Yosef and Sagiv 1982a), 2.38 (Christou et al. 1999) and 2.7 (Cavero et al. 1997). Mayfield et al. (2002) observed nitrogen deficiency symptoms at the recommended rate of 7 kg N ha^{-1} d^{-1} and recommended 'increasing total N fertilization by one-third the standard recommendation rate.' This brings into perspective the relatively high synthetic N application rates reported for tomatoes in various parts of the world.

Tomato N requirement increases dramatically during the initial fruit set stage and peaks at 50-70 days after transplanting (Fig. 1.7; Bar-Yosef and Sagiv 1982a, Sainju et al. 2000, Topcu et al. 2007, Elia and Conversa 2012). The bulk of the N (60-70%) is required when the rate of fruit development is the highest (Fig. 1.7; Bar-Yosef and Sagiv 1982a).

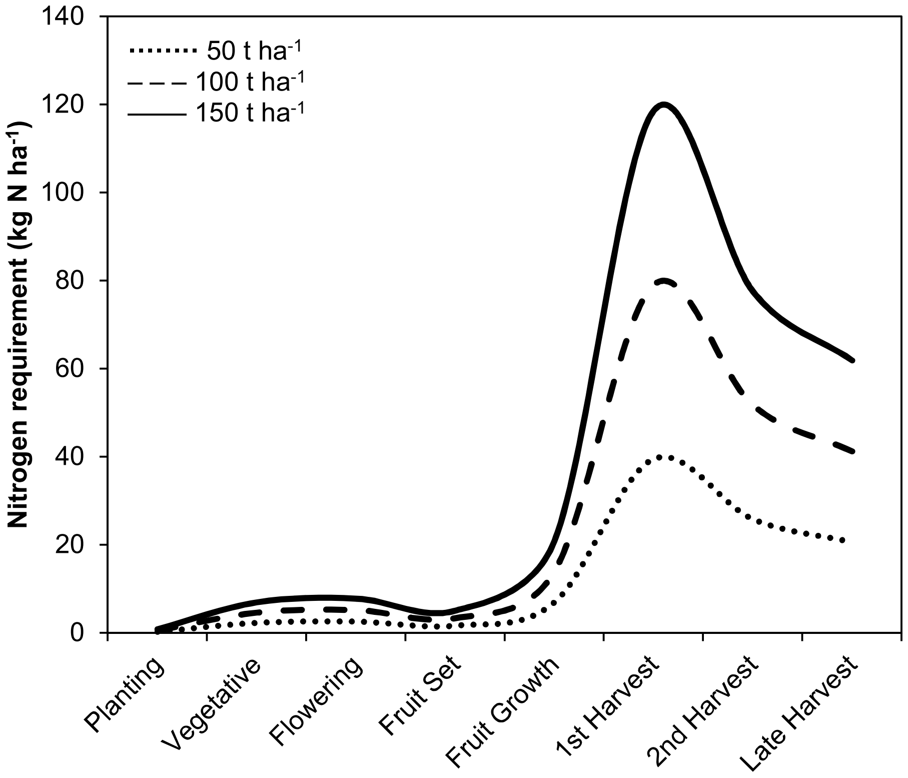


FIG. 1.7: Typical tomato N requirements during specific crop growth stages in relation to specific yield targets (50, 100 or 150 t ha^{-1}) (after www.haifa-group.com)

Around 60% of applied N ends up in the fruit (Voogt 1993). Nitrogen deficiency at the fruit development stage causes lower yield due to decreased vegetative growth and the resultant lower fruit number (Gul et al. 1996, Parisi et al. 2006, Topcu et al. 2007). Cavero et al. (1997) reported daily requirements of 3-6 kg N ha^{-1}. Bar-Yosef and Sagiv (1982a) recorded peak demand rate of 5.2 kg N ha^{-1} d^{-1} at 70 days after seeding, which decreased to 2.2 kg N ha^{-1} d^{-1} at 140 days after seeding. Tomato nutrient management programs must consider synchrony between nutrient supply and demand (Topcu et al. 2007). This is the single most critical factor in the debate regarding the use of organic or inorganic nutrient sources.

Tomato yield can be optimized provided that the intricate interaction between irrigation and fertilizing is well-managed (Phene et al. 1992, Kafkafi 1994, Hebbar et al. 2004, Warner et al. 2004, Rinaldi et al. 2007, Massa et al. 2013). This is an important confounding factor when interpreting tomato yield responses to treatments simply because fertilization and nitrogen management are suboptimal (Scholberg et al. 2000). Since the introduction of drip irrigation, nitrogen use efficiency (NUE) increased dramatically because of improved root growth (Hebbar et al. 2004, Sun et al. 2013). Optimization of fertilizer application in tomato production systems has been advocated since the 1990's (Dadomo 1994). Optimization is achieved through correct fertilizer application timing and improved methodology (Dadomo 1994). The pre-plant soil fertility status, cropping history and target yield are important factors to consider (Dadomo 1994). Key to optimization is measuring crop sap, and leaf or soil nutrient status (Krusekopf et al. 2002, Castellanos et al. 2013, Farneselli et al. 2014). In China, a combination of optimum plant nutrition and adequate defence against above-ground pests enabled tomato yields of 1.3 fold greater than the water-only control (Zhu et al. 2012). Therefore, it is not merely a matter of optimized N application rates, but rather management of an ever-expanding array of agronomical issues that influence tomato crop physiology.

1.4.3.2 Physiological responses to excessive N fertilization

Although vegetative growth responds positively to increasing N rates, excessive inorganic N application is associated with increased total yield but also increased tomato fruit quality problems, resulting in reduced marketable yield (Tabor 2001, Tei et al. 2002, Moreno et al. 2003, De Luca et al. 2006, Parisi et al. 2006, Cliff et al. 2012, Nawaz et al. 2012). In addition, flowering and fruit numbers could be reduced at high N rates (Gul et al. 1996, Elia and Conversa 2012, Nawas et al. 2012). Parisi et al. (2006) reported reduced ripeness (green fruits) and deterioration of fruit quality attributes at >150 kg N ha^{-1}. Zhang et al. (2010b) reported that for every 10-38 kg N ha^{-1} applied above the optimum rate an additional 25-28 t ha^{-1} of unmarketable fruits were produced.

Although the tomato plant responds readily to moderate fertilization, this response diminishes at excessive N application rates (> 200 kg N ha^{-1}) (Sørenson 1993, Abdul-Baki et al. 1997, Sainju et al. 2000, Elia and Conversa 2012, Sun et al. 2013). At these high application rates of N, NUE decreases, thereby increasing the risk of leaching (Rinaldi et al. 2007, Montemurro et al. 2009, Zhao et al. 2012, Sun et al. 2013). Ammonium and nitrate uptake by tomatoes do not increase with increased nutrient availability (Huett 1996). This explains why only 45-73% of applied N is taken up by tomatoes and losses of 43-67% of applied N are reported (Bar-Yosef and Sagiv 1982a, Sainju et al. 2000, Sun et al. 2013). Producers need to consider the negative environmental impact of excessive fertilization associated with the pursuit of high tomato yield.

High N rates cause an imbalance between vegetative and reproductive sinks, which cause excessive vegetative growth at the expense of fruit formation (Tabor 2001, Nawaz et al. 2012, Massa et al. 2013). Problems related to excessive N are more pronounced when climate conditions reduce the rate of fruit formation, thus tipping the source-sink balance in favour of vegetative growth (Elia and Conversa 2012). Yield and fruit quality problems linked to excessive N application are caused by disturbance of the rhizosphere osmotic potential (Huett 1996). Excessive N application suppresses calcium content in tomato fruits, probably due to source-sink competition from rapid canopy development (Dumas et al.1994, Zoes et al. 2011). Calcium is critical to prevent Blossom End Rot (BER), a fruit physiological disorder that affects the appearance and shelf-life of fruits and thus its marketability (reviewed by Saure 2001). Excessive N rates also decrease disease resistance (Nawaz et al. 2012).

Given the sensitivity to nutrient application, the obvious tomato response is luxuriant vegetative growth (Tabor 2001, Rinaldi et al. 2007). The unsustainable activity of over-application of N fertilizer causes produce defects and nutrient wastage. The constant increase in fertilizer costs and the fertilizer price shock of 2008/2009 compelled tomato growers in South Africa, and elsewhere, to investigate the feasibility of organic nutrient management approaches.

1.4.3.3 Organic nitrogen supply

Organic farming differs from conventional farming based on allowable nutrient sources to be used for fertilization (Francis and Porter 2011). A range of technologies is available for organic nutrient management: composts, manures, fresh plant material/wastes, liquid extracts or fermentates of composts/manures/plant matter, commercial or on-farm humic acid preparations, biochars, animal wastes and a host of organic industrial by-products (Creamer et al. 1996, Atiyeh et al. 2002, Lohr and Park 2007, Quilty and Cattle 2011). Tomato waste itself contains substances that promote tomato growth (Suzuki et al. 2002). The N content of the liquid organic fertilizers is often very low (Table 1.4).

TABLE 1.4: Nitrogen supply from selected organic sources as reported for open field tomato production

Organic source	N supply quantity or rate	Reference
Fish extract	0.07 kg N	Creamer et al. (1996)
Seaweed powder	0.007 kg N	Creamer et al. (1996)
Fish and seaweed powder	0.008-0.3 kg N ha^{-1}	Tourte et al. (2000)
Liquid swine manure	1.44-1.76 kg N ha^{-1} d^{-1}	Cushman and Snyder (2002)
Fish powder and seaweed	0.4-2.8 kg N ha^{-1}	Poudel et al. (2002)
Compost tea	27-104 mg N l^{-1}	Hargreaves et al. (2009)
Seaweed extract	0.03% N	Rathore et al. (2009)

Humic acid extracts from vermicomposts have differential effects on tomato seedlings (Atiyeh et al. 2002). Thus the efficacy of these liquid organic fertilizers depends on the use of large volumes, which causes water-related side-effects especially in heavy soils. Solid organic materials are the preferred source of nutrients because of high nutrient content, positive effect on other soil quality attributes, and general cost-efficiency in comparison to liquid alternatives.

The primary source of organic N for tomato plants is N mineralized from soil organic matter. However, the rate of mineralization of soil organic matter reported in literature ranges from 0 to 3.32 kg N ha^{-1} d^{-1} (Table 1.5). Regarding the meta-analysis results, estimated gross N mineralization from the soil N pool ranges from 3.6 to 75.6 kg N ha^{-1}, with a mean and median of 25.1 and 19.8 kg N ha^{-1} (Table 1.3). The total N pool ranges from 180.0 to 3780.0 kg N ha^{-1} (Table 1.3). These daily and cumulative N mineralization rates from soils are not sufficient to support tomato growth, especially during the periods of peak N demand (Fig. 1.6). In order to increase the sheer quantity of available organic N, larger quantities of exogenously added organic matter is required. Although the total N values for composts, manures and cover crops appear to be sufficient to support tomato growth, only 10-30% of this organic N pool is mineralized over time (Table 1.5).

TABLE 1.5: Expected nitrogen release from soil and organic matter amendments

Location (Climate type)	**N availability**	**Reference**
Soil	**kg N ha^{-1} d^{-1}**	
Southern France (Temperate)	0 – 0.6	Celette et al. (2009)
Australia (Tropical/Temperate)	0.02 – 0.08	Unkovich and Baldock (2008)
Northern France (Temperate)	0.42	Garnier et al. (2003)
Japan (Temperate)	2.13	Sano et al. (2006)
Compost/manure	**% of total N content**	
Laboratory incubation[a]	0.7 – 26.5	Kraus et al. (2000)
Eastern USA (Temperate)	10 – 30	Bulluck et al. (2002b)
Midwest USA (Temperate)	10 – 40	Curless and Kelling (2003)
Laboratory incubation	21.6 - 36.9	Cordovil et al. (2005)
Cover crops	**% of total N content**	
Western USA (Temperate)	5.2 – 9.5	Kuo and Sainju (1998)
Midwest USA (Temperate)	7 – 37	Fu et al. (1987)

a. Implies optimum temperature and moisture conditions were maintained for the duration of the experiment.

This explains why the N application rates for organic tomato farms in California range from 72 to 258 kg N ha^{-1} (Letourneau et al. 1996). Other reports from literature observed that yields from tomatoes grown on inorganic N was superior to the organic N supply program (Heeb et al. 2005). N supplementation is required if plants are grown in composts as growing medium (Kraus et al. 2000). Blossom end rot, a classic nutrient deficiency disease in tomatoes, is also problematic in organic tomato production systems (Sorensen and Thorup-Kristensen 2006). In order to compensate for suboptimal nutrient supply from organic matter sources, growers and researchers may be tempted to add even more organic matter to soils in order to increase the available N pool.

Excessive compost application reduces marketable tomato yield (Manishi et al. 1996, Zoes et al. 2011), fruit growth rate (Manishi et al. 1996) and rate of flowering (Togun and Akanbi 2003). Others reported inconsistent yield responses over longer periods of study (Poudel et al. 2002, Martini et al. 2004, Warman 2005). Tomatoes that receive organic matter amendments have higher number of fruits but the fruit weight is lower than the control (Ismail et al. 1996). Growth inhibition of seedlings is associated with excessive soil electrical conductivity (Diaz-Perez and Camacho-Ferre 2010). Nutrient wastage and leaching from organic sources were reported for tomato production systems. For example, Burger and Jackson (2003) reported that nitrogen contribution in an organic system was 390 kg N ha^{-1} $year^{-1}$ whereas the conventional system used 185 kg N ha^{-1} $year^{-1}$. Atiyeh et al. (2002) found the leaf N content of tomato seedlings treated with various vermicompost extracts was extreme (>6%) in all treatments - this is indicative of excessive N supply. Decomposition of high-nutrient organic residues leads to nutrient loss through leaching because of the crop's inability to utilize all the available nutrients (Gäredal and Lundegårdh 1998, Cordovil et al. 2005, Masaka et al. 2013).

The excessive supply via organic materials of macro-elements other than N poses greater plant and soil health threats over the long term. For example, Reddy et al. (2009) reported that the application of poultry manure at 200 kg N ha^{-1} in no-tillage cotton plots caused the accumulation of P in the soil. The micro-element content of composts and manures can pose greater plant health risks than the macro-element content. For example, boron, an essential micro-element for plants, is required at 0.2-1.5 ppm, yet it becomes toxic above 2 ppm (Brinton et al. 2008). Thus, if a grower aims to adjust the macro element fertilizer requirements of a crop with a high application rate of compost, the quantity of a micro-element such as boron may reach yield-limiting levels in the soil before the intended macro element requirement is fulfilled. Tomatoes are particularly sensitive to boron deficiency (Huang and Snapp 2004) and micronutrient nutrition is especially an important component of resistance to various tomato diseases (Diogo and Wydra 2007). Growers are aware of the potential risks of the overapplication of synthetic micro-element fertilizers to crop health. However, growers need to be aware that a similar risk exist regarding micro-elements when applying organic matter to soils.

1.4.3.4 Benefits of an organic component

Despite the valid criticisms against the use of organic matter in order to manage crop nutrient requirements, the non-nutrient benefits of soil organic matter are not disputed. The use of composts, manures and cover crops as soil conditioners are widely reported in literature. Soil organic matter improves the resilience of soils, thereby making these less prone to nutrient imbalances as is the case with hydroponic systems (e.g. Voogt 1993, Zekki et al. 1996, Premuzic et al., 1998, Roosta and Hamidpour 2011). Compost application has been shown to improve the calcium content of tomatoes (Manishi et al. 1996) and vermicompost is associated with increased tomato yields (Arancon et al. 2003, Zaller 2006, Gutiérrez-Miceli et al. 2007). Mixtures of composts and soil in potting growth media improved soil quality and tomato dry weight (Özdemir et al. 2007). Compost application should form part of an integrated soil quality management program. For example, Martini et al. (2004) reported that tomato yields from a wheat-tomato crop rotation were better than the compost-only treatments (90 t ha^{-1} vs 77.5 t ha^{-1} respectively). The condition of the receiving soil is also critical, and can be managed by organic matter application. For example, Rinaldi et al. (2007) reported a yield of 159 t ha^{-1} for the control treatment that received no inorganic fertilizer or irrigation and this treatment outperformed the other fertilizer/irrigation treatment combinations. The fruit quality was acceptable and the economic return of this control treatment was also superior. Thus it is important to seriously consider the impact of climate and initial soil quality/health on the ability to sustain tomato production.

1.4.3.5 Integrated organic and synthetic N nutrition

From the preceding sections it is clear that nutrient management for tomatoes is not a function of using either inorganic or organic sources, the more important factor being to satisfy the crop’s minimum nutrient demands. Over-application of N, no matter the source or target system, increases the likelihood of leaching and crop physiological disorders. Nitrogen is the major factor that affects tomato growth in comparative organic versus conventional production system experiments (Melton and Dufault 1991, Cavero et al. 1997, Pimentel et al. 2005, Sorensen and Thorup-Kristensen 2006). Even in organic tomato production systems nutrient supplementation is required to improve yields (Gäredal and Lundegårdh 1998). Insufficient soil inorganic N caused by slow mineralization of organic N, reduces leaf development but not radiation use efficiency or photosynthate production rate (Cavero et al. 1997). For this reason, tomato production systems that rely on inorganic N supply are likely to be more sustainable than systems based on organic N supply only (Bergstrom et al. 2005).

The results of the meta-analysis support these observations from literature (Fig. 1.3). The total available nitrogen per plant differentiates low and high yield/plant scenarios. At suboptimal total N supply (<167.5 kg N ha^{-1}), the contribution of organic available nitrogen (soil and exogenously added organic matter) to prevent further yield reduction is critical (scenarios 1 vs 2, Fig. 1.3). At high total available N supply (>167.5 kg N ha^{-1}), the contribution of inorganic N has to be <57.3% of the total N requirement for the target yield. The negative impact of excessive synthetic N supply is demonstrated in this meta-analysis (scenarios 3 vs 4, Fig. 1.3). The inability of solely organic matter sources to supply the tomato crop’s N requirements was established in this literature survey. However, the non-nutrient benefits of organic matter are also emphasized. This meta-analysis points to a possible optimum organic:inorganic N combination of ~40:60, which considers the high N requirement of the tomato crop while the benefits of the organic component are recognized. The key limitation of synchronous N supply with crop demand remains. The practical aspects of fertigation are a non-issue, but reliance on biological N supply via organic matter decomposition is not a trivial matter. The key problem is timing and placement of organic matter of suitable quantity and quality in the target soil. Excessive application of synthetic N prior to planting is associated with low yield (Garton and Widders 1990), as evidenced by the lower yield in the more fertile soils of scenario 6 (Fig. 1.3). Successful implementation of such a program requires intimate knowledge of the physiological processes of the crop, and the influence of climate and soil on crop nutrient acquisition behaviour.

1.4.4 Production system

The juxta positioning of conventional against organic agriculture is commonly observed in literature relating to the major crops; the tomato is not an exception. However, conflicting uses of definitions frustrate detailed analysis of these production systems. For example, tomato farming systems labelled as ‘conventional’ implemented classic organic technologies such as multi-crop rotations and even exogenous organic matter applications in the form of manures or composts (Abbasi et al. 2002, Poudel et al. 2002, Pimentel et al. 2005, Yogev et al. 2009, Giola et al. 2012). In a study by Liu et al. (2007a), organic tomato farms did not use synthetic fertilizers or pesticides, ‘sustainable’ farms used synthetic fertilizers but not synthetic pesticides, and conventional farms were characterized by monoculture, fertilizer, pesticide and herbicide use. De Ponti et al. (2012) defined conventional agriculture as ‘any agricultural system in which chemical inputs are used.’ In the 1990’s, there was a difference between *conventional* and *IPM* (Integrated Pest Management) tomato production systems (Brumfield et al. 1993): *conventional* tomato production implied cultivation in bare soil whilst the *IPM* and *organic* systems involved plastic mulch as soil cover; in current times IPM is strongly associated with conventional production systems (despite the contrary) while inorganic mulches are considered non-organic (IFOAM 2012:17). Curiously, Brumfield et al. (1993) used stakes to produce trellised tomatoes in the *organic* plot, but not in the *IPM* and *conventional* plots; today, staking is the preferred way to grow high quality fresh-market tomatoes regardless of management system. In the study by Cavero et al. (1997), tomatoes were direct seeded in the conventional plots, but transplants were used in the organic and low-input plots. Despite these inconsistencies, the most frequently used criterion for distinction between conventional and organic tomato production systems is the usage of synthetic pesticides and herbicides (Creamer et al. 1996, Poudel et al. 2002, Pimentel et al. 2005, Marinari et al. 2006, Liu et al. 2007a, Riahi et al. 2009, Francis and Porter 2011).

Poudel et al. (2002) studied four tomato production systems over five years: organic, low-input, and two conventional (2-crop and 4-crop rotation). Each system exhibited different yield patterns over time. Over the 5-year period, the average and median yields did not differ between production systems; however, the yield variance between the systems differed substantially. The low-input system provided the most stable model from a business perspective because of medium-term consistency. The organic system ranked second. However, a detailed economic comparison of the systems highlighted the ‘unfair’ price advantage that organic producers had (Poudel et al. 2001) – the organic system, if allowed to compete on equal terms with the conventional systems, was never economically sustainable in the 10-year period (Creamer et al. 1996). Similar observations were made by Turhan et al. (2008), who compared energy usage of organic and conventional tomato production systems in Turkey. The organic system was deemed more profitable, even though the cost of conventional production was 45% lower. Organic growers secured a 128% higher price per tonne for their produce, but supplied 127% less produce to the market than their conventional counterparts.

Despite the criticism against the economic aspects of the organic approach, the report by Bulluck et al. (2002b) revealed an important result. These authors compared tomato yields based on production system history and the current production system (Table 1.6).

TABLE 1.6: Effect of production system history on tomato yield (Bulluck et al. 2002b)

	Organic production (current)	**Conventional production (current)**
Conventional history	16.25 t ha^{-1}	15.77 t ha^{-1}
Organic history	37.75 t ha^{-1}	38.08 t ha^{-1}

Their results indicated that farms with an organic farming history performed substantially better than farms with a conventional farming history, regardless of the current production system. These results indicate there is merit in addressing the sustainable agriculture goals of soil health and crop rotation. Although the alternative system recorded superior yields, the overall yields were disappointing and probably not economically sustainable, especially by current South African economic standards. The challenge for South African tomato growers would be to harness and expand upon the lessons learned from this example.

Regarding the comparison of yields between organic and conventional, literature indicated that yield was 20-37% lower in organic production systems (Riahi et al. 2009, De Ponti et al. 2012). The reasons for this difference were complex but linked to the distinguishing principles of each production system. For example, nutrient management problems were typical of organic systems because of the unpredictability of nutrient release from organic sources, a problem easily avoided in conventional systems due to inorganic fertilizers. However, both organic and conventional systems faced the risk of over fertilizing. This was probably the case with the organic system described by Riahi et al. (2009) – nitrogen supply in the organic treatments were 1.7 to 2.3 times higher than the nitrogen rate recommended by conventional tomato farmers.

The type of production system was of less importance than the details of the nutrient management strategy in defining the difference between low and high tomato yield scenarios in this meta-analysis. However, the distinction between production system type was observed at high planting densities (scenarios 6 and 7, Fig. 1.2). This distinction was probably related to the more efficient N fertilization by synthetic means, whereas greater competition between plants would exacerbate challenges associated with asynchronic organic N supply. Nevertheless, aspects of organic agriculture that could be adopted by conventional tomato growers were improved management of the soil resource and reduction of unnecessary pesticide applications. Organic tomato growers could benefit from conventional practises such as improved nutrient management through the judicious use of fertilizers.

1.5 Soil biology: the final frontier?

The future of tomato production in South Africa is following international trends by intensifying through expansion into protective cultivation systems (greenhouses, nethouses, and tunnels). The reasons for this strategic shift are the need to reduce the transportation distance between farm and market, higher financial impact of severe climate events (hail, wind and insect pests), and increased socio-political pressure on rural land ownership (land restitution claims). In short, higher yields are likely to be pursued on similar or reduced cultivated areas in the near future. However, increased intensification becomes problematic if unsustainable production methods continue to be used.

In the present time there is no shortage of information about the importance of chemical and physical attributes to the effective functioning of soils and the resultant impact on crop productivity. The importance of the plant pathogenic aspect of the soil biological component is well-appreciated and remains an active research area for all crops, especially the tomato. However, the role of the non-pathogenic soil biological component in agriculture remains largely misunderstood due to its complexity (Buée et al. 2009). Biological nutrient cycling and biological disease suppression are sustainable agricultural keystones, in theory at least. Despite the relevance of the megatrends identified in this meta-analysis, the importance of biologically active soils, or 'living soils', to tomato yield and overall sustainability of tomato production systems remains unclear.

The issue of soil health and soil biological testing gained popularity among growers in recent years (Pankhurst et al. 1995, Doran and Zeiss 2000, Sherwood and Uphoff 2000, Nielsen and Winding 2002, Janvier et al. 2007, Gugino et al. 2009, Van Antwerpen et al. 2009). Indeed, the promotion of soil health in general, and biological nutrient cycling and biological disease suppression in particular, were identified by many authors as important characteristics of sustainable agriculture (Stirzaker et al. 1989, Becker and Johnson 2001, Altieri 2002, Bergström et al. 2005, Birkhofer et al. 2008, Pretty 2008, Govaerts et al. 2009, Francis and Porter 2011, Gomiero et al. 2011, IFOAM 2012:26, Lu et al. 2012, Tittonell and Giller 2013, Migliorini et al. 2014). A host of soil health metrics were used in several studies to compare the impact of conventional and organic production systems for several crops including tomatoes (e.g., Marinari et al. 2006, Tu et al. 2006, Birkhofer et al. 2008, Mazzoncini et al. 2010). However, very few of these studies, apart from those focusing on plant disease (e.g., Liu et al. 2007b), correlated the soil biological results with tomato yield (e.g. Buyer et al. 2010).

Worldwide, tomato production requires intensive application of fertilizers, pesticides, tillage, energy, and labour to provide high-value marketable produce (Davis et al. 1996, Zalom 2003, Canakci and Akinci 2006). We know that permanent agricultural activities affect soil health (Marzaioli et al. 2010). We also know that long-term monocropping encourages establishment and expansion of persistent plant pathogenic disease complexes (e.g., Li et al. 2014a). What role can 'living soils' play in this drive towards sustainable intensification? Is there a place for 'benign' microbiology in modern agriculture? Therefore, an urgent need exists to define, develop, and implement context-specific sustainable tomato production systems and technologies in Southern Africa. This is necessary to prevent medium-term damage to tomato-tolerant agroecosystems and maintain the economic sustainability of the Southern Africa tomato industry as a whole.

1.6 Conclusions

Meta-analysis was used to identify and rank the mega-trends influencing open field fresh-market tomato production. CART analysis is a valuable tool for creating a hierarchy of yield-limiting factors. Precipitation is the single most important factor that influences yield. Soil texture contributes to the distinction between low and high yield scenarios under specific circumstances (high planting density, high vs low soil fertility). Crop productivity is affected by the interaction with planting density. Nitrogen, and the balance between organic and inorganic nitrogen supply, has a significant influence on yield outcomes. Closing the tomato yield gap in the SADC region requires a strong emphasis on satisfying the basic agronomic requirements of tomato production: selection of suitable planting times based on prevailing climatic conditions, expert irrigation, effective management of excess water from rainfall, expert synthetic nitrogen nutrition (in balance with additional macro- and micro-element nutrition), selection of fields of suitable soil quality, and implementation of organic crop or soil management technologies in the short and medium term.

CHAPTER 2

ECONOMICS VS. ECOLOGY: A CASE STUDY FROM THE SOUTH AFRICAN TOMATO INDUSTRY[1]

Abstract

The tomato is a popular vegetable but its production requires above-average inputs of energy, labour, fertilizer, water, and pesticides. The objective of this case study was to evaluate the economic factors that influence the sustainability of tomato production in the South African context. A clear understanding of economic crop production factors is a necessary prelude to any discussion on ecological sustainability. Only six papers with sufficiently detailed tomato production costs for open-field cultivation of medium fruit size tomato cultivars were retrieved. This information was compared to production costs and yields of a large commercial South African tomato producer. The results show that production costs are similar between the case studies based on percentages of cost categories. Wages represents the largest cost contribution (median of 44%), followed by marketing (12%), overheads (10%), fertilizer (8%), pesticides (4%), and seedlings (4%). However, in monetary terms, the differences based on total costs and profits are substantial. Within a period of six years, South African tomato production cost per hectare more than doubled but the profit margin decreased 2.25-fold. South African tomato production costs are on par with developed world trends, but these producers receive prices half of the global trend in return. The importance of tomato quality as an economic factor is demonstrated. In order to remain economically viable, open field production systems in South Africa need to consistently deliver near-maximum yields of 120 t ha^{-1}. The Environmental Impact Quotient (EIQ) demonstrates the antagonistic and complementary interactions between economic and agro-ecological constraints. Economic pressures force tomato producers to intensify production, which underscores the need for the continued development of sustainable tomato production systems.

Keywords: Climate, Costs, Environmental impact quotient, Sustainability, Prices, Yield

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2.1 Introduction

The tomato is an important vegetable with a range of reported nutritional and health benefits. Global tomato production (tonnes) has grown by 27% from 2004 to 2013, with Asia (+60%) showing the strongest regional growth (FAOSTAT 2015). Tomato production in the Southern African Development Corporation (SADC) region demonstrated strong growth (+80%) over the 2004-2013 period. South Africa, ranked 34th in the world, is the dominant tomato producer in the SADC region, growing 41% of the tomatoes on 8% of the total hectares (Fig. 1.1).

Yield gap is defined as the difference between the potential and actual yield for a specific crop in a region. Based on FAOSTAT (2015), tomato growers in South Africa outperform their peers in the SADC region by a wide margin. It is possible to view this remarkable difference – the consistently high commercial yields vs consistently suboptimal yields - as a practical and relevant description of a crop yield gap. Based on this premise, a substantial tomato yield gap exists within the SADC region even though several countries have climate conditions suitable for open-field tomato production. Understanding the reasons behind tomato crop failures and successes in South Africa can help improve tomato production in the fast-growing tomato markets of Angola, Mozambique and Zimbabwe, thereby improving food and nutrition security for smallholders and the population in general. The objective of this work is to highlight the economic factors that govern the sustainability of the South African tomato industry. This is a necessary prelude to a discussion on the biophysical limitations of tomato cultivation in Southern Africa and its agro-ecological implications. Furthermore, this economic foundation will inform the general discourse on exactly what sustainable tomato production means for producers in the greater Southern Africa region and beyond.

2.2 Materials and Methods

A literature review was performed in order to identify the agronomic megatrends that governed high- and low-yield scenarios in organic, conventional and integrated open field, medium fruit size cultivar, fresh-market tomato production systems. A meta-analysis was performed on literature extracted from ScienceDirect and Google Scholar with the following keywords: tomato, organic, and conventional. Several hundreds of publications were retrieved and evaluated for completeness in terms of the agronomic criteria, but only six detailed reports on tomato production costs were found. Production costs were adjusted to 2013 costs in US\$ ha^{-1} to account for relative inflation. Profit was calculated as follows:

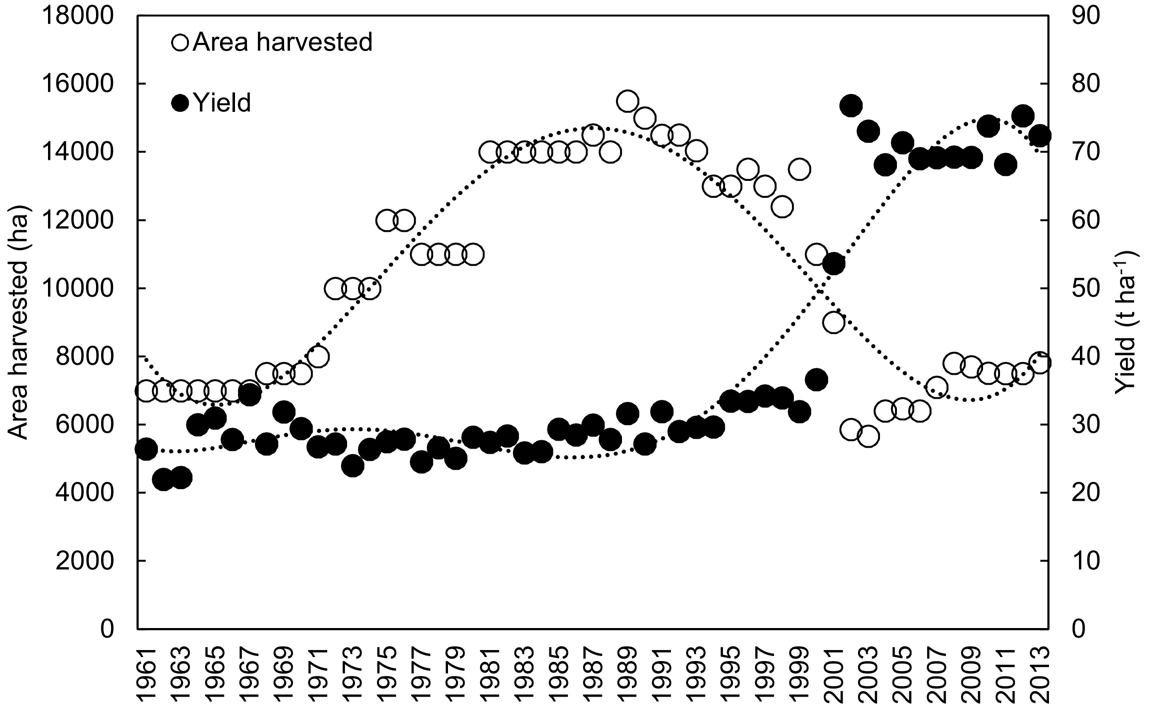
Profit margin = ((gross income – gross expenses)/gross expenses) x 100 (2.1)

Global and national tomato production statistics were obtained from FAOSTAT, South African Department of Agriculture, Forestry and Fisheries and Statistics South Africa. In addition to this, long-term production cost, yield and tomato pricing data was obtained from the largest commercial tomato producer in South Africa (www.zz2.biz). Open field tomato production activities centred around the town of Mooketsi, Limpopo province, South Africa (23^{o}36’5.95’S; 30^{o}5’37.02’E). Detailed records on all aspects of crop management (i.e., the use of biocides, pesticides and herbicides) were obtained from the commercial tomato producers in Limpopo. This information was used to calculate the ecological impact of cultivation events using the 2012 version of the Environmental Impact Quotient (EIQ) model (Kovach et al. 1992). The EIQ is a composite indicator for calculating the relative impact of agricultural pesticides on the consumer, worker and the ecosystem; only the ecosystem impact component was used in this study. Time-series and Classification and Regression Tree (CART) analyses were performed in R (packages *ts* and *ctree*; www.r-project.com). Where mentioned in the text, statistical significance was determined with the Kruskal-Wallis test ($\alpha = 0.05$) using PAST (Hammer et al. 2001); error bars represent the standard error of the means in all figures.

2.3 Results and discussions

2.3.1 Tomato cultivation in South Africa

A key feature of the history of tomato production in South Africa is a dramatic increase in yields (+110%) during the early 2000’s with the introduction of indeterminate cultivars, which allowed for sustained high-intensity production on 47% less land (Fig. 2.1). Access to agrotechnology (knowledge, synthetic inputs, information technology) further enhanced productivity where tomato cultivation was already successful.



* Dotted lines are polynomial trend curves

FIG. 2.1: Summary of tomato production trends in South Africa from 1961-2013 (FAOSTAT 2015)

Tomatoes are produced in all the provinces of South Africa with covered cultivation occurring near the major metropolitan areas in Gauteng, KwaZulu-Natal, Eastern-Cape and the Western-Cape provinces, while 75% of open field production occurs in the Limpopo Province (DWAF 2011). When compared to the main vegetables produced in South Africa, tomato production ranked 4th based on the average annual production for 2010 to 2013, but ranked 1st on the basis of income per hectare (FAOSTAT 2015, Table 2.1). R1.7 billion of revenue was generated from a mere 7 581 hectares of tomatoes per year from 2010-2013 (FAOSTAT 2015).

TABLE 2.1: Production and economic statistics for the major vegetable crops produced in South Africa from 2010 to 2013 (FAOSTAT 2015)

Vegetable	Production (tonnes)	Yield (t ha^{-1})	Price (ZAR tonne^{-1})	Income (ZAR ha^{-1})
	Average values for 2010-2013 (standard error of the means as % of the average)			
Potatoes	2 197 072 (1.7%)	34.2 (0.6%)	R2 445 (5.4%)	R83 516 (5.4%)
Soybeans	677 750 (6.8%)	1.6 (6.1%)	R3 520 (13.0%)	R5 546 (9.9%)
Onions, dry	601 694 (5.4%)	22.8 (1.1%)	R2 502 (17.9%)	R57 289 (18.9%)
Tomatoes	549 139 (2.3%)	72.4 (2.1%)	R3 099 (3.8%)	R224 397 (4.1%)
Pumpkins, squash and gourds	179 322 (1.8%)	14.2 (1.8%)	R3 672 (5.8%)	R52 102 (4.3%)
Carrots and turnips	172 296 (6.8%)	28.8 (1.9%)	R2 449 (4.5%)	R70 500 (4.4%)
Cabbages and other brassicas	141 359 (3.0%)	59.2 (2.5%)	R1 478 (11.8%)	R87 299 (11.1%)
Groundnuts	63 313 (15.0%)	1.2 (10.9%)	R6 726 (15.6%)	R7 944 (12.7%)
Sweet potatoes	58 239 (4.3%)	3.1 (3.3%)	R2 820 (11.9%)	R8 688 (10.0%)
Beans (dry)	47 483 (4.4%)	1.1 (4.2%)	R8 793 (16.0%)	R10 205 (18.5%)

The dominant commercial tomato producer in South Africa, situated in the Limpopo Province is a company called *ZZ2* (www.zz2.biz). The company employs 6 000 to 8 000 people on a permanent basis. At 160 000 tonnes of tomatoes produced annually, the company dominated the local tomato industry with its 32% market share in 2011 (FAOSTAT 2015). The average open field tomato yield of 80 t ha^{-1} achieved by ZZ2 exceeds the SADC and South African averages by 469% and 15% respectively.

During the early 2000's, the tomato producers from ZZ2 implemented a 'nature-friendly' production system in order to ameliorate the negative effects of long-term conventional farming. This production system aims to avoid the pitfalls of unsustainable industrial agriculture and unproductive organic systems, while retaining those aspects that are useful in the commercial agriculture context. According to Prinsloo et al. (2005), the main operational tenets of the production system are the following:

- Balance mineral elements in the soil
- Increase soil organic matter
- Improve soil microbial life and diversity
- Effective pest and disease management
- Optimize strategic and tactical water management

This approach to farming is not novel and aspects thereof are synonymous with a range of related farming philosophies such as Conservation Agriculture (reduced tillage, integrated pest management, integration with livestock), Kyusei Nature Farming (use of Effective Microorganisms® and fermented plant extracts), biological farming (application of microbial 'foods' to soils), and aspects of organic farming as practiced in the West (compost and compost tea).

Given the complexity of the production system, and the sustained implementation of the system since 2003, it is in the interest of the sustainable agriculture debate in general and the global tomato production industry in particular, to take note of the achievements and failures of these South African tomato producers. This particular example of eco-agriculture, or 'nature-friendly farming', as practiced by these tomato producers in South Africa, has already been described in literature, albeit superficially (Uphoff and Thies 2011).

2.3.2 A review of open field tomato production costs

Literature on tomato production costs are numerous, but detailed post-2000 open field fresh-market tomato production costs are scarce. Only six detailed studies could be found, four from the United States and one each from Turkey and India. This data was compared to that of the South African tomato producers in the Mooketsi area. The South African example demonstrated typical economic challenges of tomato producers in general. The production costs per hectare doubled within six years, but the profit margin decreased 2.25-fold (Table 2.2) and could not be attributed to a single cost factor, but was a function of changing global and local socio-economic factors. For example, for every percentage increase in oil price, agrochemical and fertilizer prices increased by 0.24 and 0.25% and this effect lasted for 28 months after the initial oil price shock (Babula and Somwaru et al. 1992).

Production costs and reported profits varied substantially between the reports (Table 2.2). Tomato producers from the Northwest United States reported the highest production costs per hectare, but also the highest profit due to very high market prices (Galinato et al. 2012). The median profit for the data reported in Table 2.2 is 30%, but this value must be interpreted with care. For example, the study by Bhardwaj et al. (2011) reported a 34% profit for tomato producers in rural India, but the \$234 ha^{-1} profit was 16.5 times lower than the median profit of \$4 000 ha^{-1} calculated from the publications reviewed. The \$2 417 ha^{-1} profit (64.4%) reported for Turkish tomato producers were 1.65 times lower than the median profit (Engindeniz 2007). Also, the 124% profit reported by Galinato et al. (2012) did not compensate for marketing and advertising costs associated with supplying a packaged product to distant urban markets, as was the case with the South African producer.

TABLE 2.2: Comparison of production costs and profits per hectare for open field fresh-market tomatoes production systems

Region	**Cost (ha^{-1})**	**Income (ha^{-1})**	**Profit (ha^{-1})**	**Price (t^{-1})**	**Profit margin**	**References**
India (2011)	$717	$960	$243	$80	34%	Bhardwaj et al. (2011)
South Africa (2005)	$15 937	$20 160	$4 223	$252	27%	ZZ2 (unpublished)
South Africa (2011)	$31 826	$35 600	$3 774	$445	12%	ZZ2 (unpublished)
Turkey (2010)	$3 249	$5 896	$2 647	$112	81%	Keskin et al. (2010)
USA California (2007)	$34 276	$45 500	$11 224	$1 400	33%	Stoddard et al. (2007)
USA Florida (2009)	$47 530	$55 130	$7 600	$1 313	16%	VanSickle et al. (2009)
USA Florida (2012)	$38 170	$18 450	$-19 720	$1 230	-52%	Sheahan et al. (2012)
USA Northwest (2012)	$67 855	$151 800	$83 945	$4 464	124%	Galinato et al. (2012)
Descriptive statistics						
25th percentile	$12 765	$15 312	$2 046	$217	15%	
Median	$33 051	$27 880	$4 000	$838	30%	
75th percentile	$42 850	$50 315	$9 412	$1 357	30%	

Labour and marketing costs dominated the cost structure in most of the studies considered here (Table 2.3). The South African production cost situation was similar to the global perspective, aside from the high marketing costs. The study on organic tomato production in Florida reported a net loss due to low overall production (12 t ha^{-1} yield) and high labour costs (Sheahan et al. 2012). In another study, the organic and low-input production systems were also less profitable than the conventional system due to high labour costs (Clark et al. 1998). The breakeven yields calculated for South African tomato producers are 2.3 and 2.6 times higher than the median breakeven yield calculated for the producers analysed for this study, and 20 times higher than the breakeven yield calculated for Turkish tomato farmers (Engindeniz and Cosar 2013). In addition to increased production costs, producer profits remain unstable due to tomato price volatility (MacDonald 2000).

While the actual agronomy-related costs (i.e., seedlings, fertilizer and pesticides) only represented 19% of total costs per hectare (Table 2.3), most research are focussed on optimizing pesticide application, fertilizer and water usage, planting density, pruning practices, and soil quality in an effort to reduce production costs (Creamer et al. 1996, Chellemi et al. 1997, Çetin and Uygan 2008, Argerich et al. 2013, Massa et al. 2013, Qiu et al. 2013). On the other hand, labour and marketing costs dominated the cost structure in most of the studies considered here (Table 2.3) and it is clear that potentially greater cost savings could be incurred by optimizing labour and marketing costs. However, such efforts were likely to strain labour-relations and local social cohesion. South African tomato producers therefore have three options for increasing profits and remain economically sustainable: reduce production costs, increase yields, or secure high prices.

TABLE 2.3: Comparative breakdown of production costs per hectare for open field fresh-market tomato production systems

Region[1]	**Wages**[2]	**Fertilizer**	**Pesticides**	**Seedlings**	**Overheads**	**Marketing**[3]	**Other**[4]
India (2011)	20%	8%	8%	7%	11%	43%	3%
South Africa (2005)	33%	8%	4%	2%	11%	25%	17%
South Africa (2011)	33%	7%	3%	4%	12%	25%	15%
Turkey (2010)	40%	11%	5%	4%	11%	0%	28%
USA California (2007)	63%	4%	7%	10%	8%	7%	0%
USA Florida (2009)	49%	8%	9%	3%	9%	9%	14%
USA Florida (2012)	57%	25%	0%	3%	0%	15%	0%
USA Northwest (2012)	67%	9%	1%	3%	9%	9%	3%
Descriptive statistics							
25th percentile	33%	8%	3%	3%	9%	8%	2%
Median	44%	8%	4%	4%	10%	12%	9%
75th percentile	60%	8%	5%	4%	10%	20%	14%

[1] See Table 2.2 for references to studies

[2] Wages included temporary and permanent staff

[3] Marketing costs included packaging materials and transport costs to markets

[4] Miscellaneous expenses (e.g., maintenance, depreciation)

2.3.3 South African tomato prices

Tomato production in South Africa appears to be a lucrative business given the potentially higher income per hectare when compared to the other important vegetable crops (Table 2.1). In a mixed-rotation farming experiment in the USA, the economics of the different farming systems tested were strongly influenced by the costs and profits associated with the tomato production component (Clark et al. 1999). In a similar study in Ohio (Northwest United States), the conventional system was costlier to operate than the sustainable technologies tested, but the conventional system was mostly superior in terms of profitability because of higher yield and quality (Creamer et al. 1996).

South African tomato price trends are in line with the international trend but international tomato prices are substantially higher than prices offered by the South African consumer (Fig. 2.2).

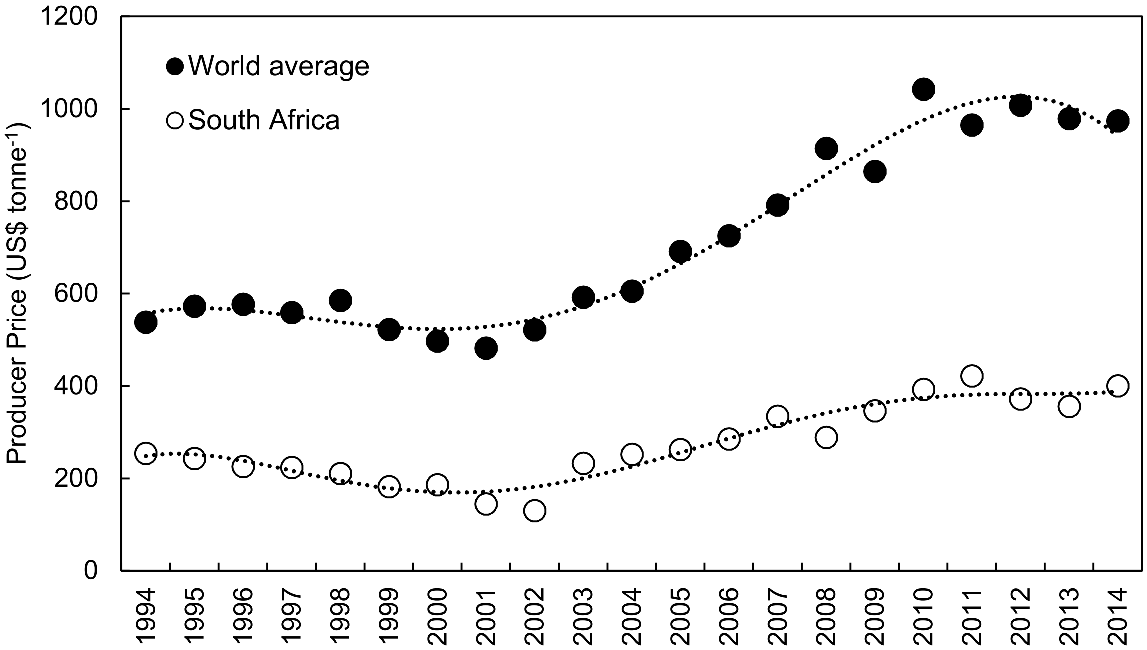


FIG. 2.2: South African tomato price dynamics in comparison to global price trends (FAOSTAT 2015)

An international tomato trade modelling study showed that Africa remains the cheapest place to produce tomatoes, but distance from the large consumer markets and import tariffs forced its prices to be on par with tomato producing regions in the developed countries (Guajardo and Elizondo 2003). However, at the local South African level, annual and seasonal price variation is at times substantial and indicates increased volatility in local tomato pricing dynamics since 2006 (Fig. 2.3). Medium-term forecasting indicates that the South African tomato prices are likely to stabilize and even increase slightly, provided the fundamental socio-economic drivers of tomato consumption do not change (Fig. 2.3).

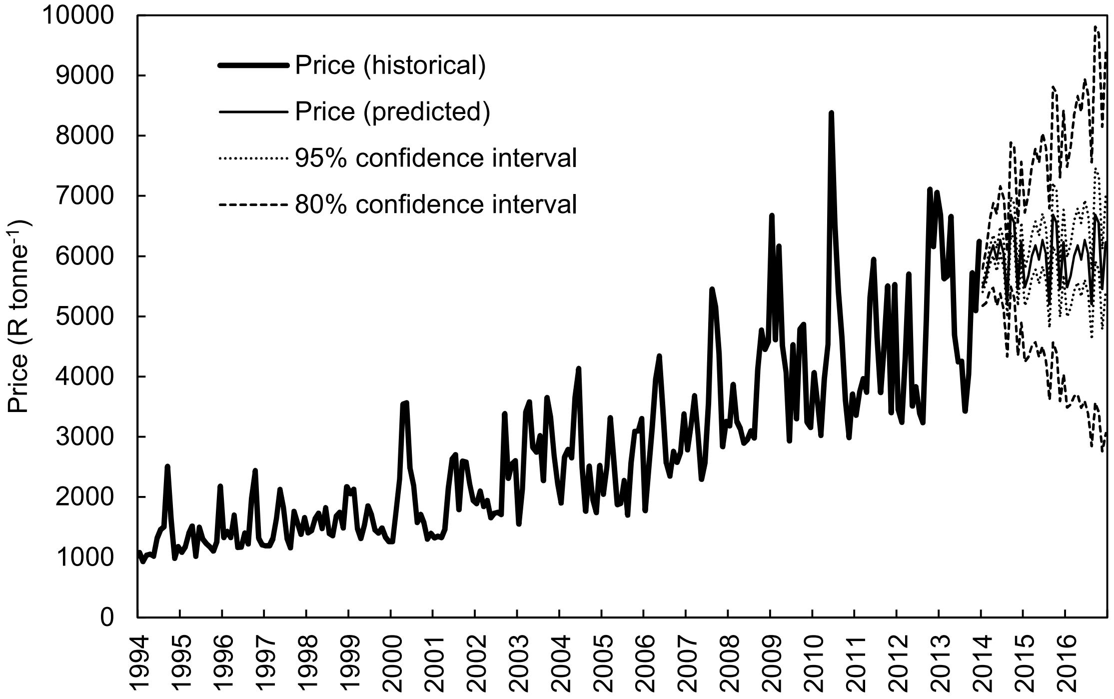


FIG. 2.3: Time series analysis of medium fruit-size variety tomato prices for South Africa showing the main trend, the medium-term forecast and the confidence intervals associated with the forecasted price trend (ZZ2, unpublished).

As mentioned earlier, economic sustainability of tomato production in South Africa hinges on three interacting factors: total production costs (economy of scale), yield per hectare (agronomic excellence) and market price (market share and differentiation). Economic sustainability can be achievable provided production costs are low, the market price is high and agronomic performance is good (Table 2.4).

TABLE 2.4: Income from tomato farming in South Africa as a function of production costs, marketable yield, and market prices[*]

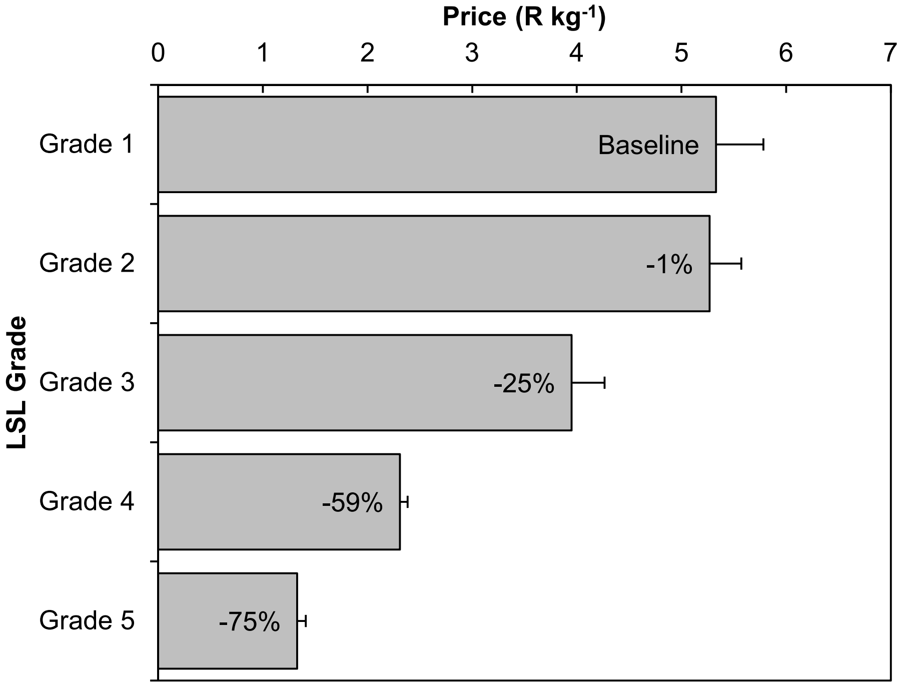
		Yield ($t\ ha^{-1}$)						
		20	**40**	**60**	**80**	**100**	**120**	**140**
Input cost per hectare in 2005: R160 000 ha^{-1}								
Price ($R\ kg^{-1}$)	**1**	R-140 000	R-120 000	R-100 000	R-80 000	R-60 000	R-40 000	R-20 000
	2	R-120 000	R-80 000	R-40 000	R0	R40 000	R80 000	R120 000
	3	R-100 000	R-40 000	R20 000	R80 000	R140 000	R200 000	R260 000
	4	R-80 000	R0	R80 000	R160 000	R240 000	R320 000	R400 000
	5	R-60 000	R40 000	R140 000	R240 000	R340 000	R440 000	R540 000
	6	R-40 000	R80 000	R200 000	R320 000	R440 000	R560 000	R680 000
	7	R-20 000	R120 000	R260 000	R400 000	R540 000	R680 000	R820 000
Input cost per hectare in 2011: R320 000 ha^{-1}								
Price ($R\ kg^{-1}$)	**1**	R-300 000	R-280 000	R-260 000	R-240 000	R-220 000	R-200 000	R-180 000
	2	R-280 000	R-240 000	R-200 000	R-160 000	R-120 000	R-80 000	R-40 000
	3	R-260 000	R-200 000	R-140 000	R-80 000	R-20 000	R40 000	R100 000
	4	R-240 000	R-160 000	R-80 000	R0	R80 000	R160 000	R240 000
	5	R-220 000	R-120 000	R-20 000	R80 000	R180 000	R280 000	R380 000
	6	R-200 000	R-80 000	R40 000	R160 000	R280 000	R400 000	R520 000
	7	R-180 000	R-40 000	R100 000	R240 000	R380 000	R520 000	R660 000

[*] Shaded cells indicate income loss scenarios

The scenario outlined in Table 2.4 indicates that higher demands are placed on plant performance when cost conditions deteriorate; higher yields are required to reach the breakeven level, especially when prices are low. Production costs doubled within a six-year period with a significant impact on the producer.

For example, a 60 t ha^{-1} harvest is considered average by pre-2000 standards, but by 2011 this yield target is profitable only if very optimistic prices (>R6 kg^{-1}) are secured. Fresh market prices have not kept pace with production costs and this forces producers to pursue higher yields (>100 t ha^{-1}) to avoid economic loss. Furthermore, since the tomato is an annual crop, production costs have to be covered from profits gained during the previous season. Sudden financial ruin is a significant risk for South African tomato producers who use developed world production technologies but receive developing world prices in return. This dilemma is not unique to the South African tomato producer. In northwest United States, VanSickle et al. (2009) estimated the production cost of an 11.3 kg carton at \$10.84 carton^{-1} (in 2008). Producers would have made a 36% loss when offered the 2006/7 price of \$7.88 carton^{-1}, but at the 2007/8 price of \$14.88 carton^{-1}, profits would have increased by 72%.

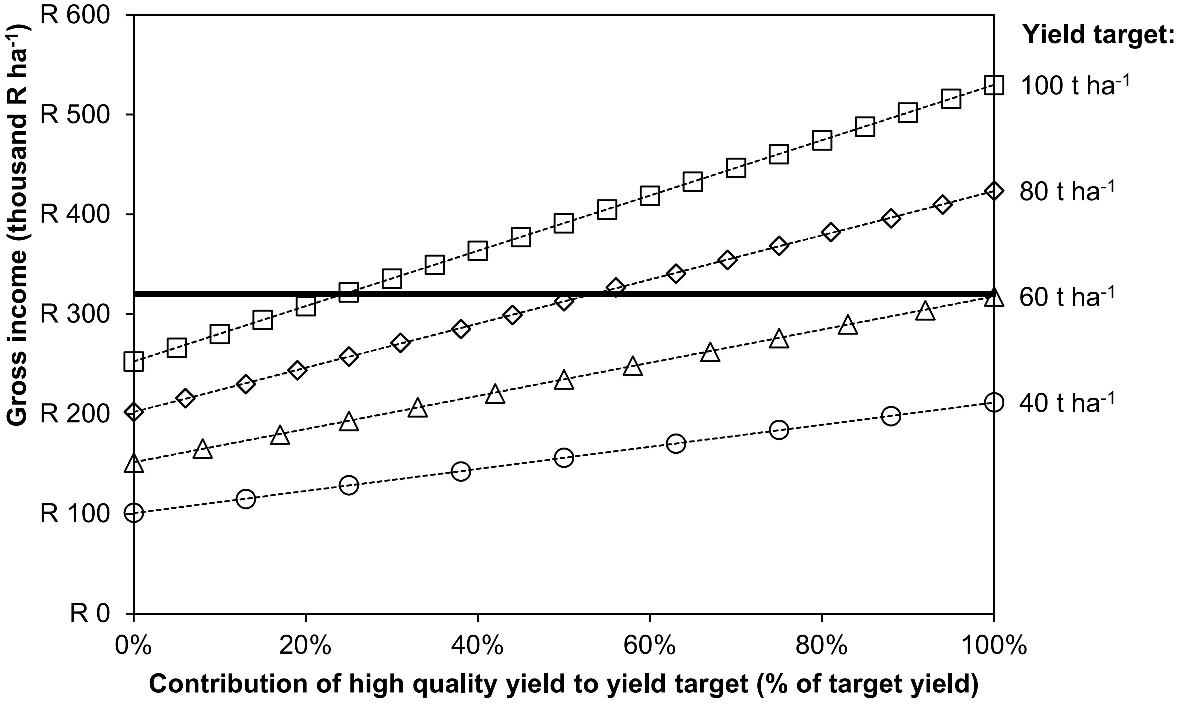
The fact that the price of tomatoes is sensitive to differences in quality grades further complicates the producer's income situation (Fig. 2.4).



* LSL = long shelf life fresh salad tomato variety; percentages indicate difference in price from Grade 1 price; error bars = standard error of the means for 2011.

FIG. 2.4: South African National Fresh Produce Market tomato prices in 2011 according to quality

Tomato fruit size also has a major influence on price (e.g., Abdul-Baki et al. 1992). In South Africa, the prices of different quality grades for medium fruit size variety tomatoes differ significantly ($P < 0.01$), which means the distribution of quality grades within the marketable yield profile exerts an important influence on the final gross income (Fig. 2.5).



[*] Horizontal line is the R320 000 ha^{-1} breakeven point used for open field fresh-market tomato production in South Africa in 2011 (Table 2.4). Gross incomes were calculated from 2011 grade-specific prices. High quality yield comprises Grades 1 and 2 only.

FIG. 2.5: Contribution of quality grades to overall economic sustainability of tomato production

Customer preferences determine which varieties are in demand and this in turn motivates the producer to pursue production of specific cultivars. For example, in the United States, marketable yield of hybrid varieties is higher than heirloom varieties, but heirloom varieties are in greater demand due to consumer preference with better resulting economic benefits (Rogers and Wszelaki 2012). American consumers prefer fresher locally grown tomatoes over more mature produce from distant markets (Bierlen and Grunewald 1995). An overemphasis on high quality produce must be guarded against. In developing countries, especially the rural areas, demand for high quality produce can be low due to unavailability; the supply of affordable food is more important and ‘lesser’ qualities are accepted by poor consumers (Cadilhon et al. 2006, Dixon and Isaacs 2013). Even in a developed country context, American consumers are less concerned about production method (organic vs conventional), but more concerned about tomato type and price (Simonne et al. 2006).

Production volumes are influenced by climate and agronomic factors which eventually influence tomato prices. For example, Mexican producers supply the American and Canadian markets, but acute shortages in the United States caused by climate-related crop failures, create local shortages in Mexico, which cause prices to rise; the opposite occurs with overproduction in the American region and local Mexican prices decrease sharply because of the inability of Mexican producers to compete with locally-produced American tomatoes (Humphries 1993). Pricing issues dominated the resulting 'tomato wars' between American and Mexican producers in the 1990's (Thompson and Wilson 1996, Girapunthong et al. 2004). The supply and demand fluctuations in Mexico and the USA are caused by climate shocks and result in price volatility.

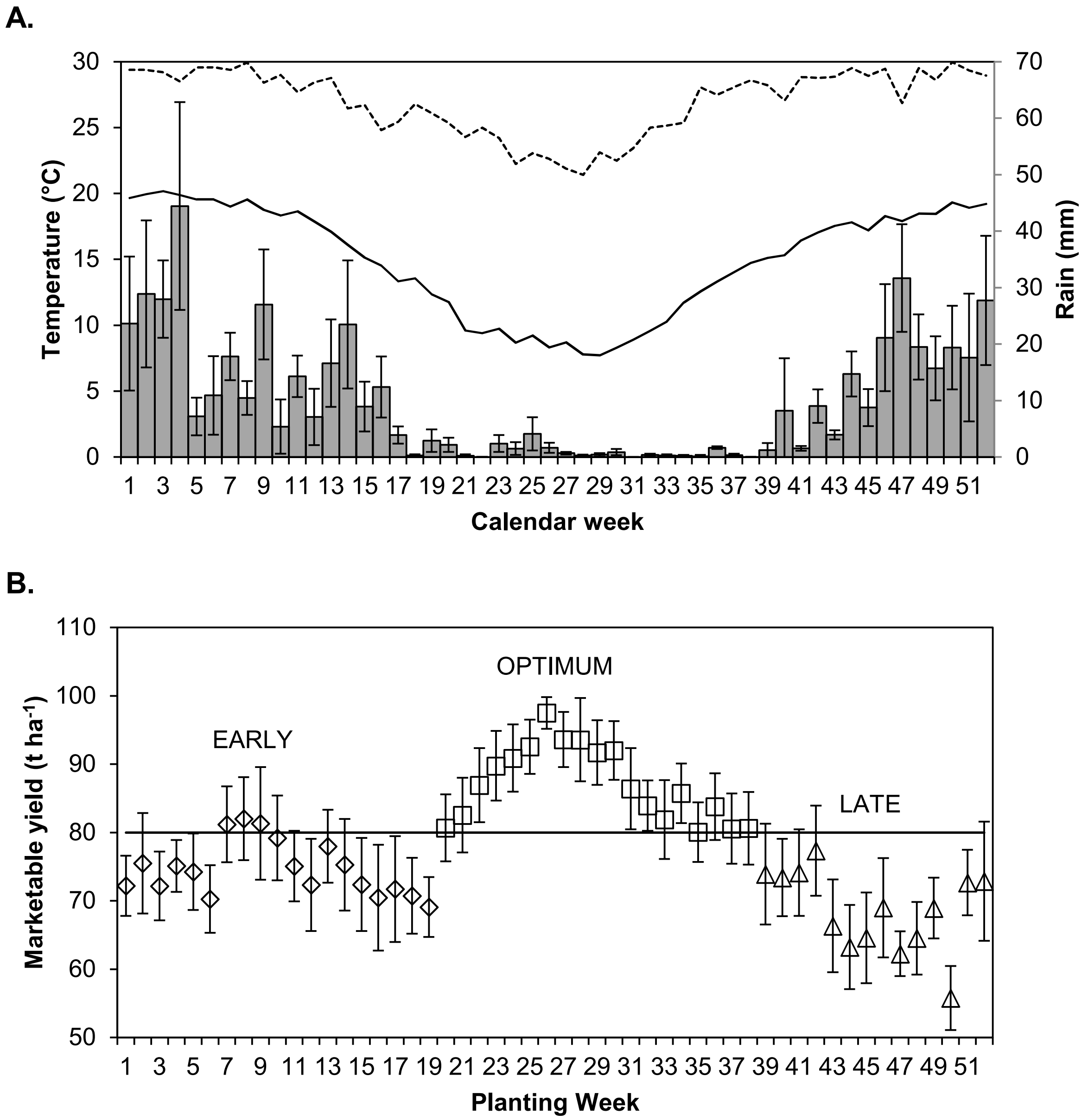
A similar situation was reported elsewhere in the world (Garg et al. 2008, Tadesse et al. 2014). In India, producers bear the brunt of price fluctuations: 'When there is huge production, price of tomato reduced very sharply. At that time producers bear huge losses because they even could not cover their production cost' (Bhardwaj et al. 2011). For this reason, some called for moderate tomato price intervention/stabilization in order to safeguard emerging producers against marketplace turmoil (Jayne 2012). In South Africa, the minimum wage for farm workers increased by 52% in March 2012, which generated calls for set minimum market prices for agricultural products. Indeed, rice price stabilization is an important aspect of rural development in Asia (Dawe and Timmer 2012) and is recommended for maize in Sub-Saharan Africa (Galtier 2013).

Non-climate factors also influence tomato prices at the local level. The current global economic crisis impacts food prices and consumer buying power, which results in changed food acquisition behaviour (Regmi and Meade 2013). Despite the importance of climate in determining agronomic performance, and market dynamics by implication, additional non-crop related factors limit tomato production, such as unexpected wage increases, urban pressure on traditional tomato growing regions, and competition from other supply regions (Weliwita and Govindasamy 1997). This high degree of uncertainty influences the economic viability of both the organic and conventional tomato producer (Lien et al. 2007). Market share, management system philosophy, and economies of scale are non-agronomic factors that improve the resilience of vulnerable farming enterprises (Lien et al. 2007, Pannell et al. 2013). Producers respond by reducing risk (through cost reduction), increasing productivity (production process optimization), and pursuing specific market opportunities (niche exploitation) (George 2013). However, the pursuit of profit at the expense of ecosystem 'health' remains a controversial issue.

2.4 Economy vs ecology

Out-of-season supply is an important factor that encourages tomato producers to persist with unsound agronomic or ecological activities (Vawdry and Stirling 1996, Peillón et al. 2013). In the 1990's, American and Mexican tomato producers worked towards multi-season supply by having geographically distributed production centres that allowed exploitation of local climate conditions for continuous supply (Thompson and Wilson 1996). In Zimbabwe, tomato production in the rainy season is associated with high fungicide usage to prevent crop failure, but the rainy season crop secures prices 10 times higher than tomatoes produced during the dry times of the year (Cooper and Dobson 2007). Manipulation of irrigation allows for earlier fruit ripening, thereby enabling early harvesting and provided the producer the ability to avoid competitors when tomato prices are high (Topcu et al. 2007). Likewise, Turkish producers are encouraged to first 'find their markets before they plant the first seed' (Engindeniz 2007). In China, irrigation-related cost thresholds were relaxed when prevailing tomato prices were lucrative (Zheng et al. 2013). Abdul-Baki et al. (1996) investigated the use of cover crops to provide sustainable solutions to intensive tomato production methods. They found that cover crops extended the growth season by three weeks, with 40% of the marketable yield being harvested in that extended time period, whereas the control treatments ceased to yield at that time. This meant distant markets, with traditionally higher prices at the particular time of the year, could be serviced with substantial economic returns.

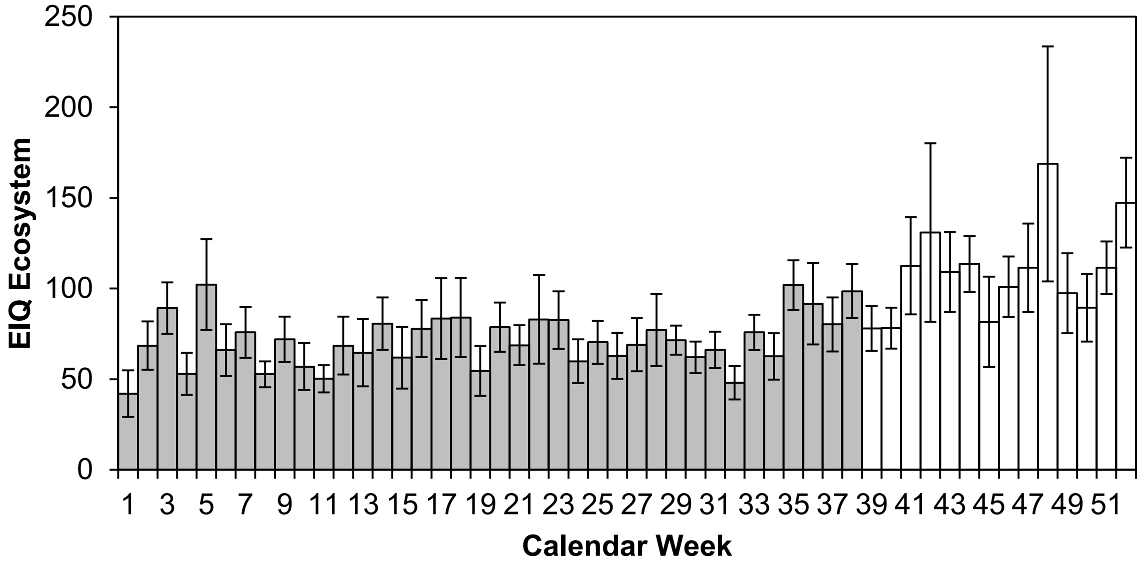
The lure of high tomato prices also convinces South African tomato producers to persist with agronomic activities within a very risky climate window. In the Lowveld agroecological zone of South Africa, the summer production season starts after year-week 39 (late September) and is characterized by summer rainfall, high temperatures and humidity (Fig. 2.6a). Marketable yield and fruit quality are severely affected as a result (Fig. 2.6b).



* The difference in yield between planting times (early, optimum and late) was significant (Kruskal-Wallis $P < 0.001$). The horizontal line on (B) indicates the 80 t ha^{-1} breakeven yield.

FIG. 2.6: The interaction between climate (A) and marketable yield (B) in the Lowveld agroecological region for 2003-2010 (source: ZZ2).

The combination of these hostile climate conditions determines the onset and intensity of physiological stress and below- and above-ground diseases. Producers are forced to intensify pest- and disease-control programs in this planting window. The weekly EIQ (ecology) score for late planting times increases by 51.6% from a mean of 72.1 to 109.4 ($P < 0.001$; Fig. 2.7).



[*] The mean Environmental Impact Quotient (EIQ) for late planting times (white bars) differed significantly (Kruskal-Wallis P<0.001) from the early and optimum planting times respectively (grey bars).

FIG. 2.7: Influence of planting time on ecosystem impact quotient of weekly synthetic pest- and disease-control interventions*

Therefore, the ecological footprint of the pest- and disease-control programs increase significantly as producers attempt to maintain high yields in the climatically challenging planting window. The duration of rotations is reduced because transport costs force producers to concentrate production activities close to packaging facilities. Planting in fields with known soilborne pest and disease problems exacerbate the situation further.

In this example, the belief that planting tomatoes in a difficult climate window is necessary in order to secure high prices has merit (Fig. 2.8).

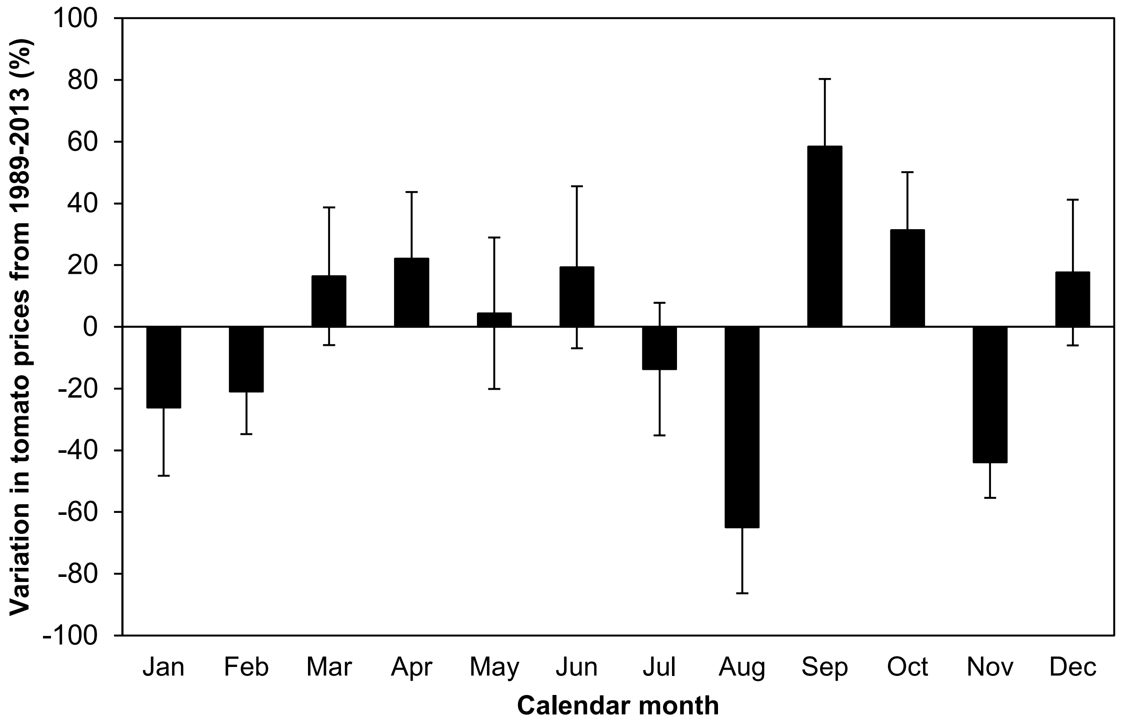


FIG. 2.8: Tomato price variation from the annual average for the period 1989-2013

Although data analysis reveals that tomato prices are extremely volatile in the short-term (up to +/- 20-30% for any given week), an above-average price tendency exists when fields planted in late planting times are harvested 15-25 weeks later in March and April the following year. The cost structure of 2005 allowed for profitable farming at low yields (Table 2.4), thus it was worthwhile to persist with late plantings and incur the resultant negative ecological impact. However, from 2011 onwards this was no longer the case. Production costs doubled and market prices remained between R4 kg^{-1} and R5 kg^{-1} on average (Fig. 2.3), thus making any tomato farming activity in the late planting time unprofitable (Table 2.4). As a result, these producers no longer utilize the late planting period for economic gain. In this example, increased economic stress (i.e., increased production costs and stagnating prices) had an unexpected ecological benefit.

2.5 Lessons for the global tomato-producing community

Intensification of tomato production is a global phenomenon and is fuelled by different driving forces. The influence of production costs for open field tomato production was reviewed, but the growing demand from consumers is another factor that needs to be considered. The rapid spread of supermarket outlets in rural areas of Latin America increased the number of potential tomato consumers, thus encouraging intensification of existing tomato production systems

(Reardon and Berdegue 2002). The trend is similar in other developing regions of the world for agricultural commodities in general (Reardon et al. 2003, Louw et al. 2007). As a result, supermarkets are becoming major stakeholders in the food production network (Dolan and Humphrey 2000, Emongor and Kirsten 2009).

Indeed, supermarket tomato price fluctuations are a function of competition between supermarkets during peak demand times, while farm-side input costs fluctuations have very little influence on the retail price (MacDonald 2000). Intensification of production is likely to become the norm in the future as production costs increase and market prices stabilize. This study about South African tomato producers is a case in point. The quest for increased yields is likely to come at the expense of ecological and social sustainability with increased pressure on soil, water, the agrolandscape, and the workforce. The relatively high tomato prices encourage the pursuit of profit and highlight the economic cost of failure.

Although marketing activities improve the customer value proposition, the producer has little influence on the actual price secured at the market. Price premiums can be secured by providing high quality products to niche markets (e.g., cherry tomato varieties) and other forms of differentiation from competitors (e.g., ‘nature-friendly’, ‘organic’ or ‘socially-responsible farming’ labels; Creamer et al. 1996, Poudel et al. 2001, Lien et al. 2007). However, the producer has for the greater part a high degree of control over the crop’s agronomic performance. Given this high degree of economic uncertainty, the South African tomato producer’s greatest responsibility is to attempt continuous supply of suitable quantity and quality of produce. Given the cost constraints faced by the South African tomato producer, the importance of tomato yield to the economic success of the farming enterprise is undeniable. These economic drivers of tomato cost of production and retail prices are likely to recur in the SADC region as regional economic growth continues to gain momentum in the next decade.

This study highlights the complex interaction between economics, agronomy, and ecosystem impact. Tomato production will intensify as production costs increase and prices remain fairly high. The ecological impact of synthetic pest- and disease-control programs increases as producers pursue challenging cultivation windows in order to meet their economic requirements. Further intensification through protected cultivation strategies will reduce the negative impact of climate and above-ground insect pests, but persistent monoculture will increase the burden on the soil resource in the long run. However, the ecosystem impact will be lower if it is not necessary to pursue near-maximum yield targets. But will the commercial producer be satisfied with an ‘ecologically sustainable yield’? Humphries (1993) warned against supra-commercialized unsustainable food production because the desire for profit will drive production, at the expense of old-fashioned ‘traditional’, or sustainable, production systems centred on basic local food supply. Indeed, in the large-scale commercial production environment, marketing and sales decisions dominate agronomic and ecological considerations (Thompson and Wilson 1996). Thus, the stage is set for continued conflict of interest between the economic and ecological aspects demanded from sustainable agriculture.

Today there is no shortage of protagonists of sustainable agriculture. However, many proposals appear far-removed from the socio-economic realities of real-world farming, especially in underdeveloped countries. In South Africa, much emphasis is placed on the potential contribution of smallholder producers to future food security. However, this case study shows that the economic and ecological aspects of sustainable farming need not be in opposition, but disregard for one will endanger the other. There is a place for ‘sustainable big agriculture’ given the ability of large commercial operations to mitigate economic and ecological risks based on their geographic footprint and ability to access and generate intellectual capital; smallholders are defenceless against these onslaughts.

This chapter focused on economic aspects of sustainable tomato production in the South African context. The lessons learned by these tomato producers may apply to potential tomato producers in the SADC region and beyond. It highlights the fact that sustainable agriculture is crop specific – what works for one crop context may not be applicable to another. However, when talking about sustainable agriculture, especially sustainable tomato production, sooner or later we have to talk about yield. This case study demonstrates that it is critical to understand the agronomic factors that limit and promote tomato yield, yet what is agronomically possible may not be economically feasible. Furthermore, given the importance of tomato quality on gross income and economic sustainability, it is necessary to understand the factors that influence the tomato quality profile within a planting event. The development of sustainable yet intensive production systems must continue while solutions to the economic drivers of unsustainability are pursued.

CHAPTER 3

THE INFLUENCE OF CLIMATE VARIABILITY ON TOMATO YIELD IN THE LIMPOPO PROVINCE (SOUTH AFRICA)

Abstract

South Africa is the leading tomato producer in the Southern Africa region. A clear tomato yield gap exists regarding the commercial yields attained by South African tomato growers compared to the rest of the region, even though climate conditions are suitable for tomato production in several neighbouring states. Understanding the reasons behind tomato crop failures and successes in South Africa can increase tomato production in the fast-growing tomato markets of the region. The objective was to study climatic variation within three climatically distinct planting windows and interactions with tomato yield and quality. The leading commercial tomato producer in the Lowveld bioregion of the Limpopo province supplied climate, yield, and tomato quality data for 2 138 production events for the period 2003-2010. Climate data was summarized according to five-week growth stage-specific phases for every production event: before planting (P0), seedling establishment (P1), initial flowering and fruit set (P2), and three consecutive five-week harvest periods (P3-P5). Interactions between climate variables and tomato yield were explored with Classification and Regression Tree (CART) analysis. The results show that different sets of climate variables influence the final yield and quality outcomes for each planting window. Temperature-related variation in the P5, P3, and P1 development phases influence total yield in the early (from summer to winter), optimum (winter to spring) and late (spring to summer) planting times respectively. Temperature, wind speed, and relative humidity are the main drivers of quality variation throughout the year. The benefit of non-damaging cold conditions for improved tomato quality is demonstrated. The five-week summary, in conjunction with CART analysis, is useful for identifying specific climate variables and their interactions with tomato yield and quality. Possible remedial actions to safeguard tomato yield or quality in the face of climate variability are early planting, early maturing varieties, and the use of synthetic/organic pest control measures and microbiological inoculants.

Keywords: CART analysis, Interactions, Planting times, Quality

3.1 Introduction

South Africa is the dominant tomato producer in the Southern Africa Development Corporation (SADC) region. South African tomato farmers produced 41% of the tomatoes from 8% of the total hectares in 2013 (FAOSTAT 2015). Tomato production ranked fourth in the South African vegetable production sector in 2013 (FAOSTAT 2015). Although tomatoes are cultivated in every province of South Africa, 75% of open-field production occurs in the Limpopo province (DWAF 2011). The average yield of South African tomato producers far exceeds that of the other tomato producing regions within the SADC region: 72 t ha^{-1} vs 3-13 t ha^{-1} respectively. There is a clear tomato yield gap within the SADC region even though climate conditions are suitable for tomato production in several countries. Understanding the reasons behind tomato crop failures and successes in South Africa can increase tomato production in the fast-growing tomato markets of Angola, Mozambique and Zimbabwe.

The tomato plant thrives in warm (20-27°C), windy and low atmospheric moisture conditions, but is very sensitive to excessive heat (>30°C), and prolonged cold and water stress conditions (Levy et al. 1978, Holder and Cockshull 1990, Hanna 1999, Hanson et al. 2000, Horchani et al. 2008). These characteristics allow for selection of production locations and planting windows for tomatoes. Within- and inter-year climate variation significantly influences tomato yield and quality. American tomato producers identified ‘weather’ as a consistent yield-influencing factor (Bauske et al. 1998). Climate conditions during the production cycle directly influences irrigation management (Helyes et al. 1999). In Brazil, climate change projections downgraded the importance of some typical tomato pests and diseases, but the economic impact of others increased (Ghini et al. 2008). The work of Maršić et al. (2005) demonstrates the dominating influence of climate on tomato production. In that study, six salad tomato cultivars were grown in two regions: region 1 (Dragonja Valley) had a warm, dry and windy microclimate, whereas region 2 (Ljubljana) was cold at night with regular rainfall. The yield in the Dragonja valley was 2.6-fold higher than yields obtained in the cold and wet region. Although there was an 80% increase in yield when tomatoes were produced in covered structures in the Ljubljana region, the overall contrast between the regions in terms of yield remained stark. The distinguishing features of experimental production systems are clearly observable when climate conditions are optimal, but yield-limiting climate events, such as early frost, sustained cloud cover, or excessive rainfall, nullify systemic differences in most instances (Abdul-Baki et al. 1996, Teasdale and Abdul-Baki 1998, Arnes et al. 2013).

The tomato is a high-value vegetable, especially in temperate regions where tomato production is limited by suboptimal temperature and solar radiation. Thus, tomato producers in suitable locations attempt to extend the production window and their ability to supply to these distant, but very lucrative markets in the temperate regions (Alvino et al. 1990, Cuartero and Rodriguez 1994, Hansen et al. 1999). The simplest of these interventions involve basic farmer wisdom: cultivate the right crop, in the right soil, at the right time of the year. However, global climate phenomena (i.e., El Niño Southern Oscillation, ENSO), regional economic pressures, and deteriorating soil quality/health at the farm-level, force farmers to cultivate their crops in degraded soils during sub-optimal times of the year. The result is a deviation from expected agronomic and economic performance and this threatens the economic and ecological sustainability of the farming entity.

Studies on planting time optimizations are still encountered in scientific literature for a range of crops (Sacks et al. 2010, Kamkar et al. 2011, Braunack et al. 2012, Elnesr et al. 2013). Planting times are revisited mainly to understand mechanisms behind recurring yield gaps for important crops at regional or national levels. The overarching drive is to address local food security, regional competitiveness on the export market, and optimize resource use efficiency. Such studies often uncover actionable shortcomings at the producer level, especially small-scale or subsistence farmers, which if addressed, lead to dramatic yield improvements. Planting time optimization for South African tomato production has not been described in scientific literature. The objective of this study is to determine the climatic factors that influence tomato yield and quality in the Lowveld bioregion of the Limpopo province as influenced by different planting times. It is hypothesized that climate variation is the leading cause of yield variation in the production region, especially during sub-optimal planting times.

3.2 Materials and methods

3.2.1 Tomato production region

Botswana, Zimbabwe and Mozambique border the Limpopo province of South Africa to the west, north and east respectively. All the tomato farms in this province are located in a summer rainfall area of the Savanna biome (Mucina and Rutherford 2006). Because of the concentration of long-term tomato production activities, our investigation focusses on a specific bioregion within the Savannah biome called the Lowveld. The tomato production fields are centred around the town of Mooketsi (23^{o}36’5.95”S; 30^{o}5’37.02”E).

The area is dominated by a single vegetation type, the Tzaneen Sour Bushveld, and is located 631-832 m above sea-level (Mucina and Rutherford 2006). The mean annual precipitation (781 mm), mean annual temperature (19.7°C), mean annual frost days (1 day) and mean annual potential evaporation (2 097 mm) enable year-round tomato production. According to the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC 2012), the dominant soils types of the study area are Acrisols (low fertility soils with high clay content), Luvisols (high fertility soils with high clay content in subsoils) and Regosols (weakly developed mineral soils without diagnostic horizons).

3.2.2 Tomato production system

A range of tomato commodities can be produced in the Lowveld region, but this study will only focus on the production of medium sized tomato fruits for the fresh market. Fields intended for tomato cultivation were cleared, ploughed and ridged 12 weeks before planting date. Fields were three hectare (ha) in size. The average planting density was 11 500 plants ha^{-1}; after pruning, the final plant density was 23 000 fruit-bearing stems ha^{-1}. Soil conditioners (such as compost and manures) were applied at varying rates within the ridges. Six-week-old indeterminate cultivar tomato seedlings were transplanted into the ridges and fertigated via drip irrigation as per standard practice (Nzanza et al. 2012). Plants were cultivated using a stake-and-trellising system. Standard pruning practices were followed in order to optimize yield and fruit size. Pest and disease control were performed in accordance with growers' pest management programs and was based on weekly scout reports. First harvest of fruit started 10-12 weeks after planting and continued until 25 weeks after planting. Fruits were cleaned, graded and packaged at regional packing facilities before being transported to the major local fresh produce markets. Plant growth was terminated after 30 weeks with herbicides and field decommissioning involved removal of irrigation and trellising infrastructure, destruction of plant material by burning, and levelling of ridges. Fields were abandoned to naturally recover for periods of one to 10 years before the next cultivation event. No dedicated task-specific crop rotations were practiced.

3.2.3 Data sets

Historical total yield and quality profiles (five quality grades) and detailed climate records from four weather stations were supplied by the producers for the eight-year time period (2003-2010). Only final yields for each cultivation event were available as outcome variables (as opposed to weekly harvest data). Producers indicated that the economic breakeven yield was

80 t ha^{-1} in 2012 and this figure was used to delineate the planting time as 'early' (planting from summer to winter), 'optimum' (planting from winter to spring) and 'late' (planting from spring to summer). The final dataset contained 2 138 production events for the early (707 entries), optimum (1 032), and late (399) planting times.

Fresh-market tomato quality is a crucial determinant of the selling price secured on the national fresh produce markets (Chapter 2). Total yield therefore cannot be used as the only measure of success. High quality yield (HQ yield) was included as an additional yield-related variable and was calculated as the t ha^{-} of First and Select grades combined – the remainder was assumed unmarketable:

$$\text{High Quality Yield (HQY, t ha}^{-1}\text{)} = \text{First Grade (t ha}^{-1}\text{)} + \text{Select Grade (t ha}^{-1}\text{)} \qquad (3.1)$$

In this context, the definition of tomato quality was based on appearance only and not the nutritional content.

The detailed climate data was obtained from four Davis Vantage Pro2 (Hayward, California) weather stations. Fields were located within eight kilometres of the nearest weather station. The daily average, minimum and maximum values were recorded for the following variables: temperature, solar radiation, wind speed, wind chill, relative humidity, atmospheric pressure, dew point and atmospheric evaporative demand; precipitation was recorded as average and cumulative daily rainfall. The Growing Degree Days (GDD) was calculated from the following tomato-specific, physiologically important temperature limits: optimum (T_{opt} = 25°C), maximum (T_{max}= 35 °C), minimum (T_{min} = 14 °C), and base (T_{base} = 12 °C). The following formulas were utilized:

$$\text{Delta T} = T_{max} - T_{min} \qquad (3.2)$$

$$\text{Growing Degree Days (GDD)} = (T_{max} + T_{min})/2 - \text{Tomato } T_{base} \qquad (3.3)$$

$$\text{Weekly Heat Units (HU)} = \Sigma \text{GDD}_i \text{ where } i \text{ is the calendar week} \qquad (3.4)$$

It is not common practice to consider chilling or cumulative cold units in tomato production. The influence of cold temperatures on tomato productivity was, however, considered by several authors (Zotarelli et al. 2009, Elizondo and Oyanedel 2010). For this reason, cold units were calculated as well:

$$\text{Weekly Cold Units (CU)} = \Sigma(14 - T_{min})_i \text{ where } i \text{ is the calendar week} \qquad (3.5)$$

Temperature data was summarized on a year-week basis, hence multiplication by seven where necessary. Due to the complex nature of the dataset and the duration of a typical tomato growing season, the data were summarized on a calendar week (year-week) basis. This simplified the data handling aspect of this study. For example, the GDD value was calculated on a daily basis but was pooled to give a cumulative weekly value (for a given calendar week of the year); the weekly GDD values were pooled to provide cumulative GDD values for a typical growth season (e.g. 25 weeks) or used to construct climate summaries for specific growth stages of the tomato crop (described below).

Data for a total of 26 climate variables were available for analysis. However, this represented a challenge given the 25-week duration of a typical tomato cultivation event. For example, different combinations of yield-limiting or -enhancing climate events could occur at any time during this 25-week period. For this reason, the climate dataset was divided into six five-week climate summaries for each of the 26 climate variables. Each five-week period corresponded roughly to important tomato development milestones (Table 3.1). Thus, 168 crop growth stage-specific climate summaries (26 climate variables, 6 crop development phases), unique for every planting week (PW), were available for multivariate statistical analysis.

TABLE 3.1: Summary of climate variables for every planting week according to five-week tomato crop development milestones

Phase (Abbreviation)	**Description**	**Notation**[a]	**Tomato crop development milestone**
Phase 0 (P0)	5 weeks before planting	WAP -5 to (-1)	Prepared soil
Phase 1 (P1)	5 weeks after planting	WAP 1-5	Early vegetative growth
Phase 2 (P2)	5 weeks before first harvest	WAP 6-10	Initial flowering and fruit set
Phase 3 (P3)	1st 5-week harvest period	WAP 11-15	First harvest period
Phase 4 (P4)	2nd 5-week harvest period	WAP 16-20	Middle harvest period
Phase 5 (P5)	3rd 5-week harvest period	WAP 21-25	Final harvest period

[a] WAP = weeks after planting

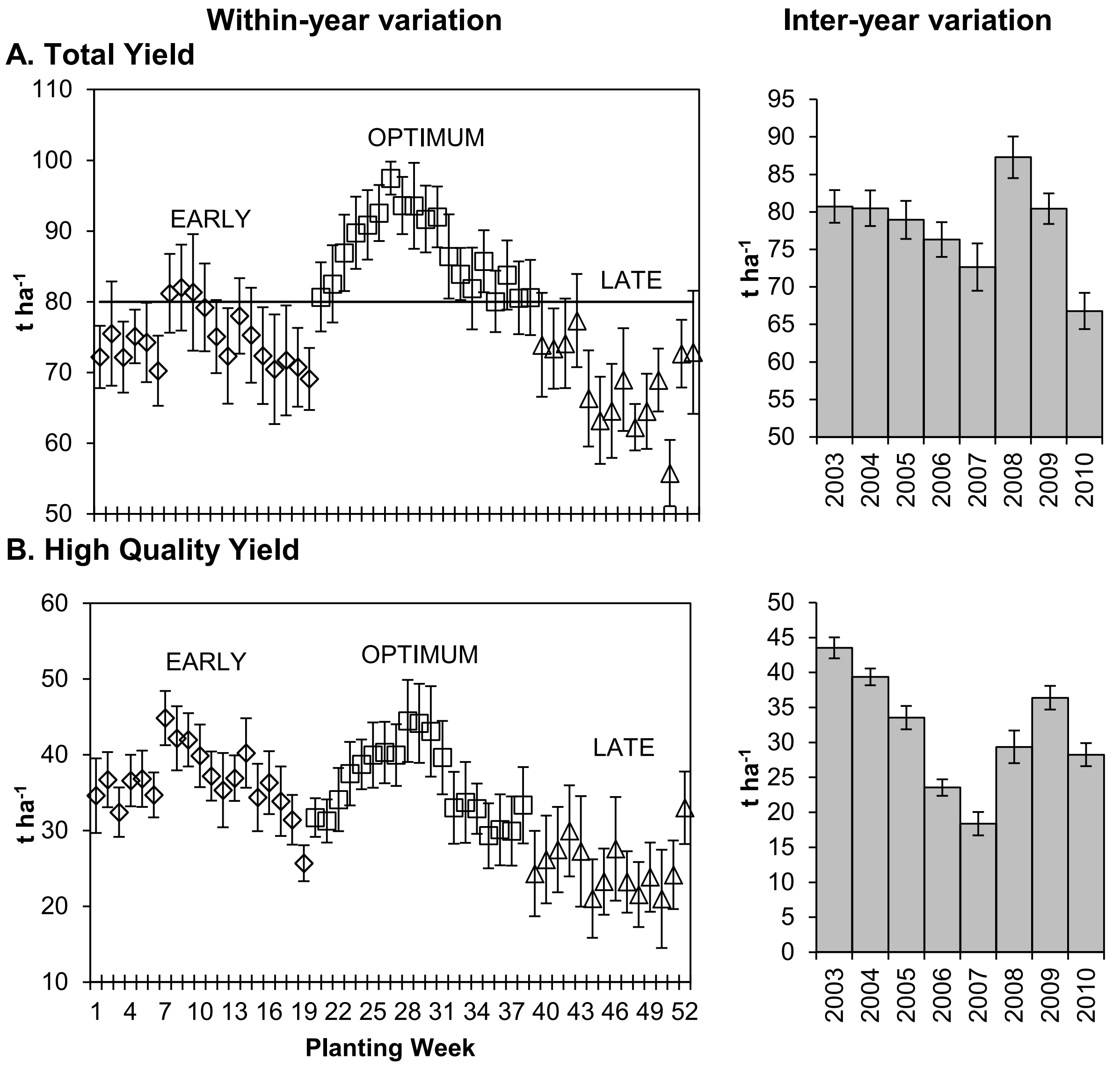
3.2.4 Data analysis

Statistics were done with the following programs/methods: univariate statistics and between-group principal component analysis (PCA; PAST 2.17b, Hammer et al. 2001); correlation matrix principle component analysis (ADE-4, Thioulouse et al. 1997); classification and regression tree (CART) analyses (*ctree* package, www.r-project.com); boundary line analysis (quantile regression method). Statistical significance was established at α = 0.05. Error bars indicate the standard error of the means (SEM).

3.3 Results

3.3.1 Inter- and intra-year variation in yield and quality

Farmer yield and climate records were used to create a summary of within-year yield outcomes (Fig. 3.1) and the main climate factors (Fig. 3.2) associated with tomato production in the Limpopo province.



Within-year variation

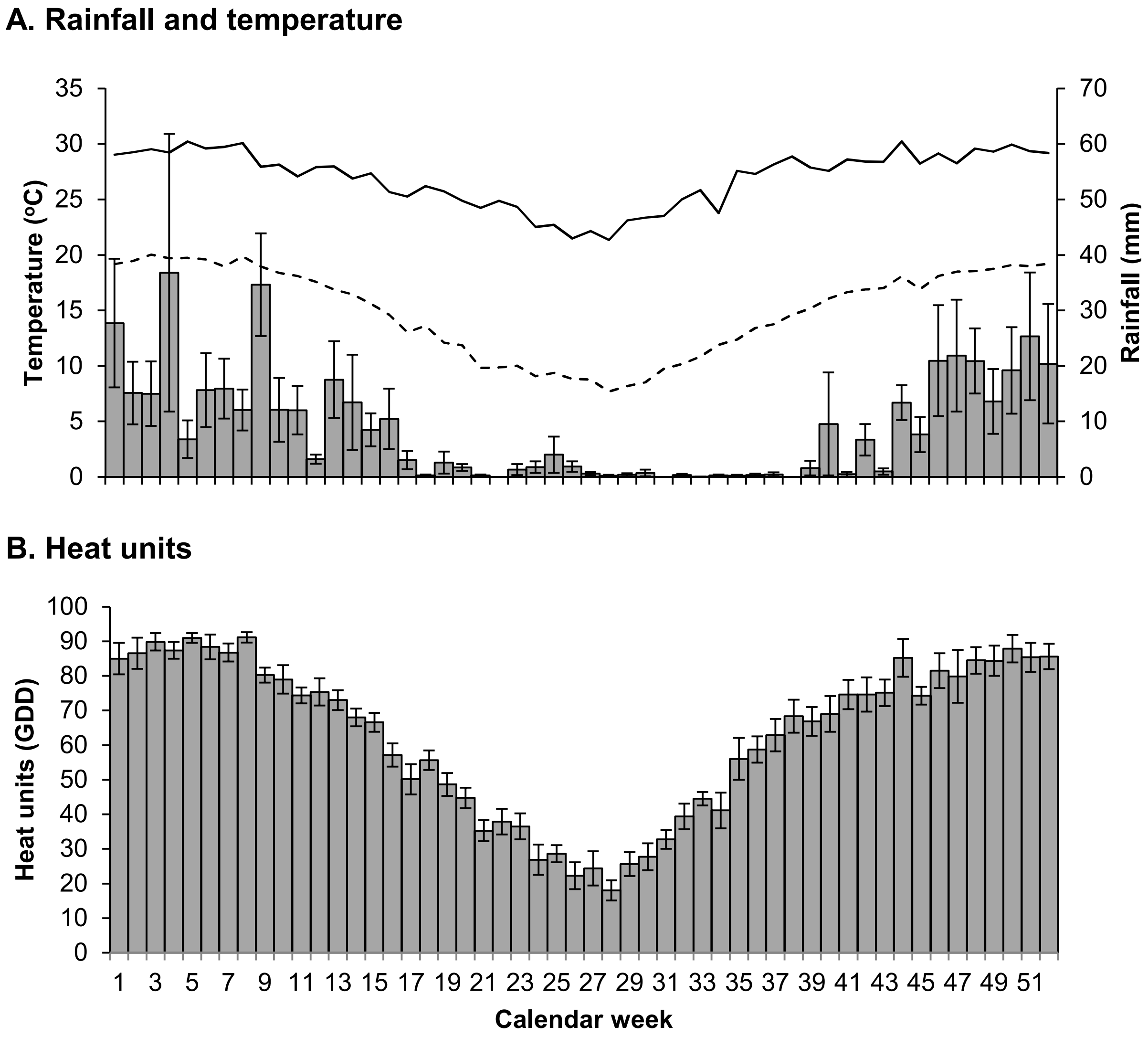
Inter-year variation

A. Total Yield

B. High Quality Yield

* Horizontal line in A marks the 80 t ha^{-1} breakeven yield. The yield data represents the cumulative yield after the conclusion of the 25-week cultivation period associated with the original planting week.

FIG. 3.1: Summary of inter- and within-year variation of total (A) and high quality (B) tomato yield during different planting times in the Lowveld for 2003-2010



* The solid and dashed lines in (A) represent the maximum and minimum temperatures respectively. Error bars represent the standard error of the mean.

FIG. 3.2: Weekly summary of temperature and rainfall (A) and cumulative heat units (B) in the Lowveld for 2003-2010

Records from 2 138 production events confirmed that year-round tomato cultivation occurred in the Lowveld region of the Limpopo province. However, agronomic success, as measured by total and high quality yield outcomes, was inconsistent throughout the year (Fig. 3.1). The best agronomic planting time appeared to be around PW 20 to 38; the risk of a low total yield and poor quality profile was very low during this period (Fig. 3.1). The onset of the summer rains from week 40 onwards was associated with low total yield and poor quality outcomes (Fig. 3.2). The early planting period (PW1-19) was risky in terms of total yield expectations, but the quality profile was more favourable than the late planting period despite the regular occurrence of rain.

Cumulative heat units or growing degree-days (GDD) is an effective yield predictor for many crops. For tomatoes, a range of cumulative heat units required for optimum yields is reported in literature (Table 3.2).

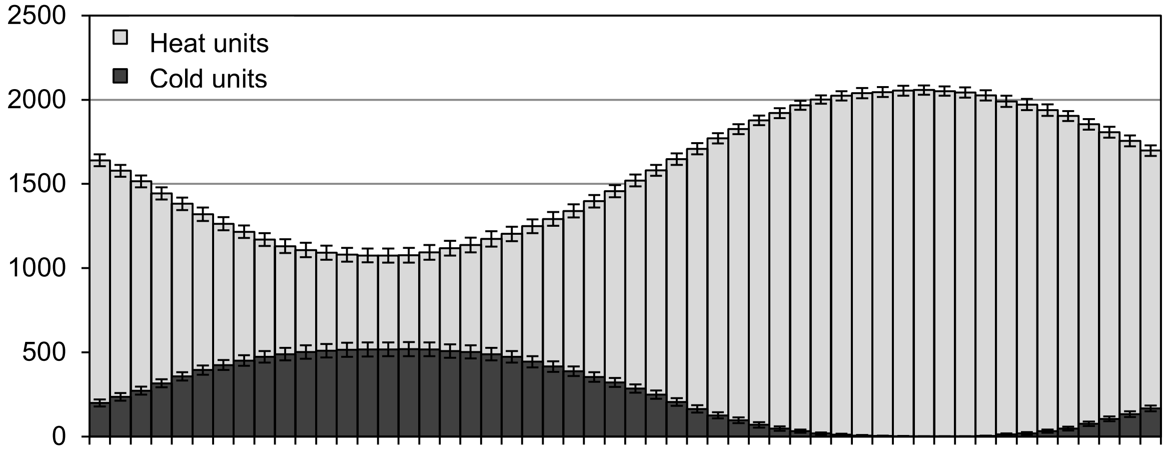
TABLE 3.2: Growing degree days for optimum tomato productivity

GDD (°Cd)	**Reference**
702 - 1 046	Elizondo and Oyanedel (2010)
799 - 1 752	Pogonyi et al. (2005)
800 - 1 000	Zotarelli et al. (2009)
1 000	Islam and Khan (2000), Aldrich et al. (2010)
1 400	Scholberg et al. (2000)
1 993	Katerji et al. (2013)

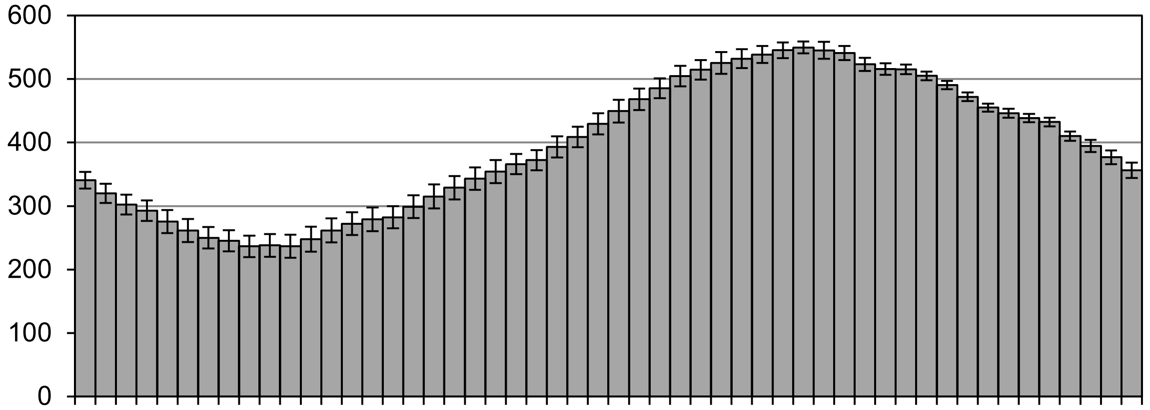
Teng et al. (2012) could not demonstrate correlations between GDD and tomato yield. Discrepancies in GDD limits originate from different calculation formulae (reviewed by Perry et al. 1997), the use of different base temperatures, and differences in cultivar tolerance to heat or cold temperatures. However, Wolfe et al. (1989) corrected GDD data for maximum temperature impacts, which resulted in an improved correlation with yield. The values reported in Table 3.2 are lower than the GDD values reported in this study (Fig. 3.3), except for those reported by Katerji et al. (2013). Thus it appears that GDD is not a viable tool for predicting tomato yield, but the occurrence and duration of heat spells is an important factor to consider.

Nevertheless, a summary of the main yield-influencing climate variables according to the 25-week duration of a typical tomato production event indicated that the late planting period was exposed to high cumulative rainfall and heat units (Fig. 3.3). Although the tomato crops were produced under drip irrigation, the onset of the rain season was associated with increased disease and pest pressure. The early planting time exposed tomato seedlings to decreasing cumulative rainfall and heat units, with a concomitant increase in cumulative cold units. The optimum planting time exposed seedlings to increasing cumulative rainfall and heat units, while the risk of exposing crops to cold stress decreased towards the onset of summer.

A. Cumulative heat and cold units (GDD, ºCd)



B. Cumulative atmospheric evaporative demand (mm)



C. Cumulative rainfall (mm)

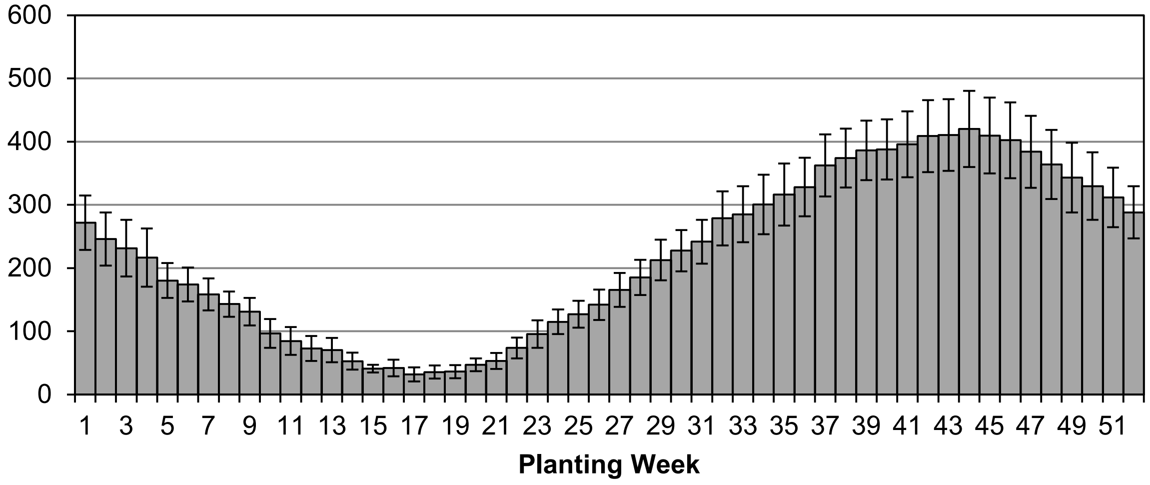


FIG. 3.3: Cumulative temperature (A), atmospheric evaporative demand (B) and rainfall (C) based on the 25-week duration of a growing event for the given planting week (2003-2010). Error bars represent the standard error of the means (SEM) for the period.

Principal Component Analysis (PCA) of the correlation matrix confirmed the extent of inter-year yield and quality variation (Fig. 3.4 and Fig. 3.5).

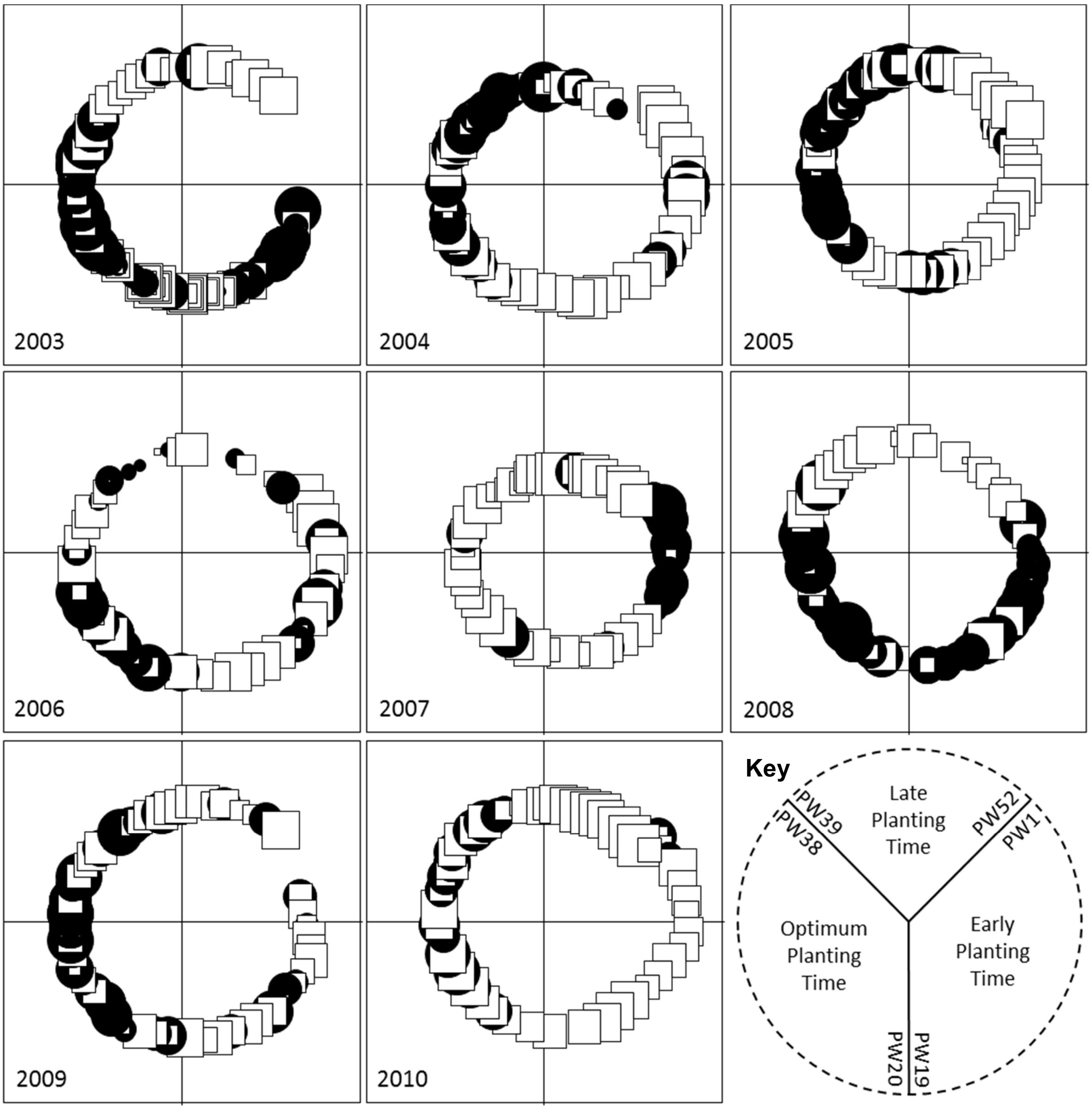


FIG. 3.4: A summary of the total yield responses associated with annual climate variation for 2003 to 2010 as determined by principal component analysis. The factorial maps represent the 25-week climate summaries for production events associated with each planting week (see Table 3.1). The first component accounted for 40.1% of the variation in the dataset and the second component another 29.0%. Standardized yield and quality data was projected onto the factorial maps, where circles and squares represent above- and below-average yields respectively. The size of the symbols is relative to the distance from the dataset mean – the larger the symbol, the greater the distance from the dataset mean. The position of the symbols corresponds to the different planting times as indicated in the key.

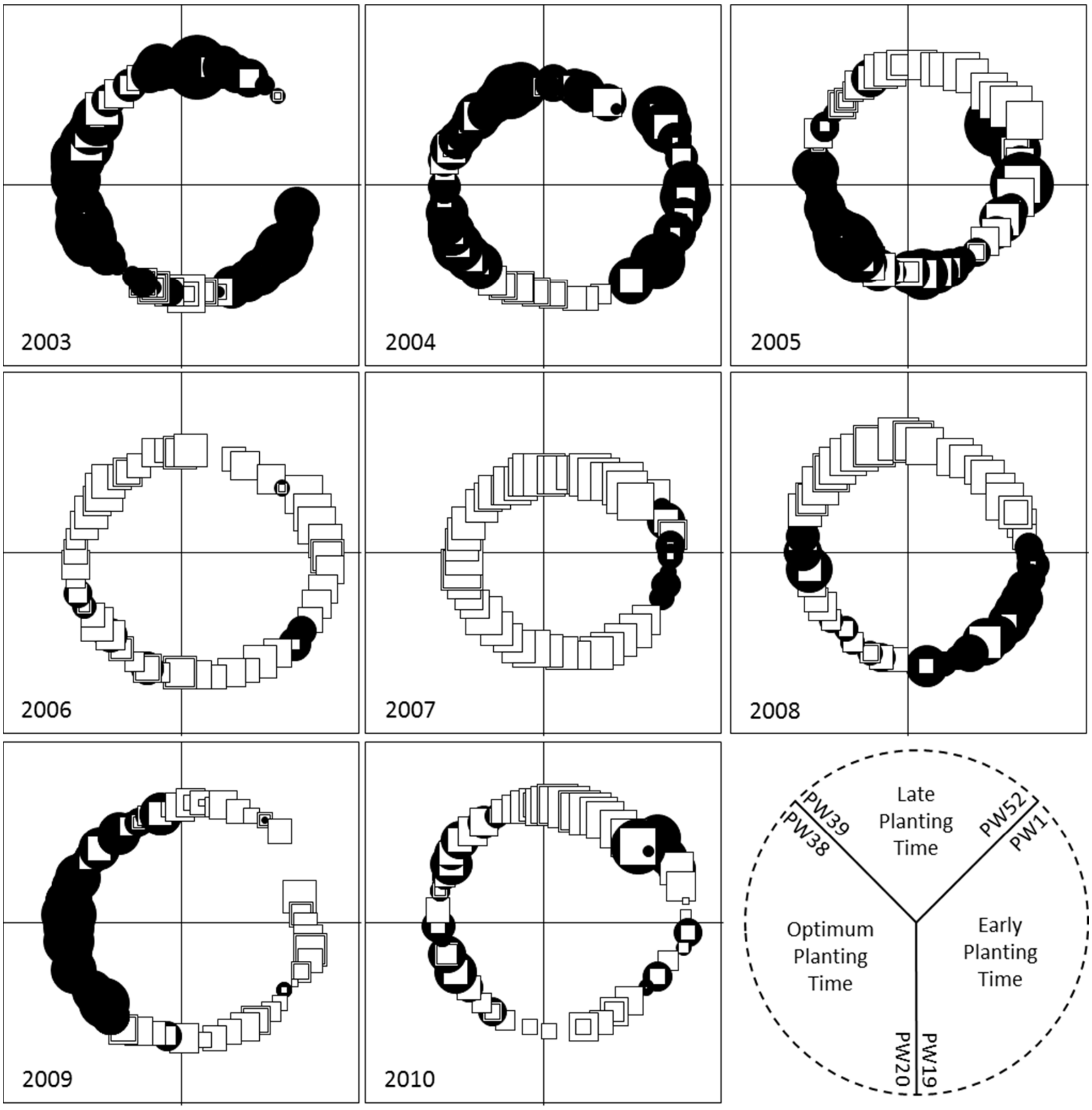


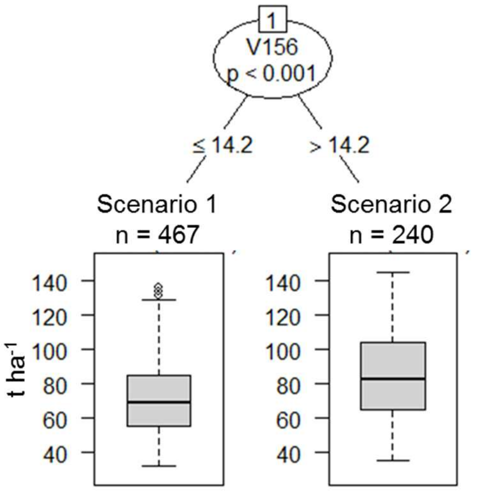
FIG. 3.5: A summary of the marketable yield responses associated with annual climate variation for 2003 to 2010 as determined by principal component analysis

The PCA results indicate that yield and quality fluctuations were not consistently associated with a specific planting period, but rather occurred during different periods of the year. Therefore, in order to appreciate the influence of climate (and by extension planting time selection) on tomato yield and quality, a detailed analysis of growth stage-specific climate variability is required.

3.3.2 Early planting time

Differentiation between low and high total yield during the early planting time was attributed statistically to a single climate variable: average delta T during the final five-week harvest period (P5 ΔT, Fig. 3.6A). For the early planting time, in 66.1% of instances, total yields were lower when P5 ΔT ≤ 14.2ºC; for the remainder the total yields were higher when P5 ΔT > 14.2ºC (Fig. 3.6A). This observation provided a suitable explanation for inter-year variation in total yield for this planting window (Fig. 3.6B and Fig. 3.6C).

A. CART analysis result



[*] Vertical axes represent high quality yields; Legend to (A): V156 (P5 ΔT, ºC); all splits and levels were shown.

B. Total yield

C. P5 ΔT (ºC)

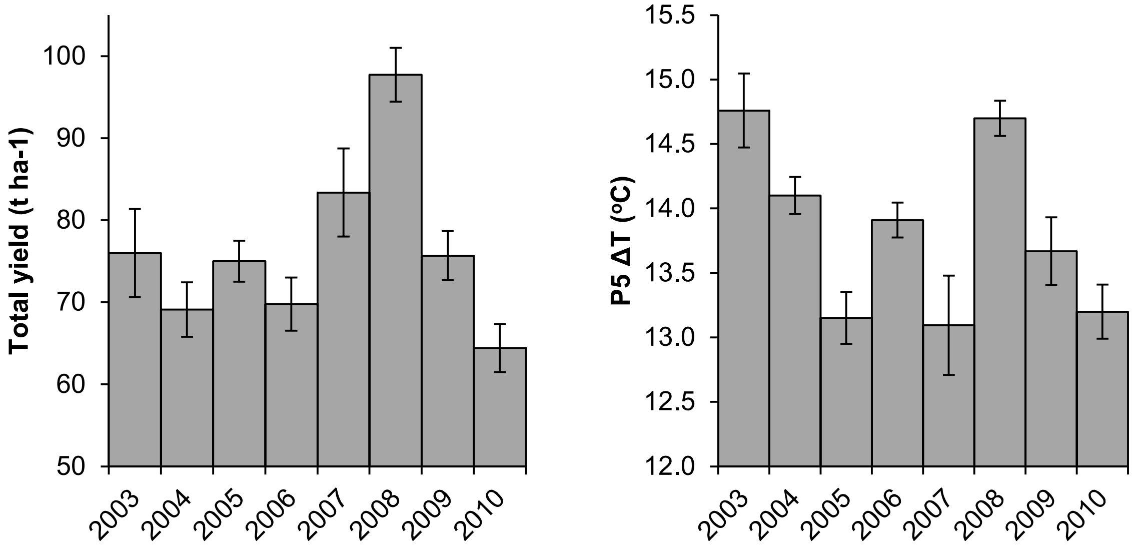
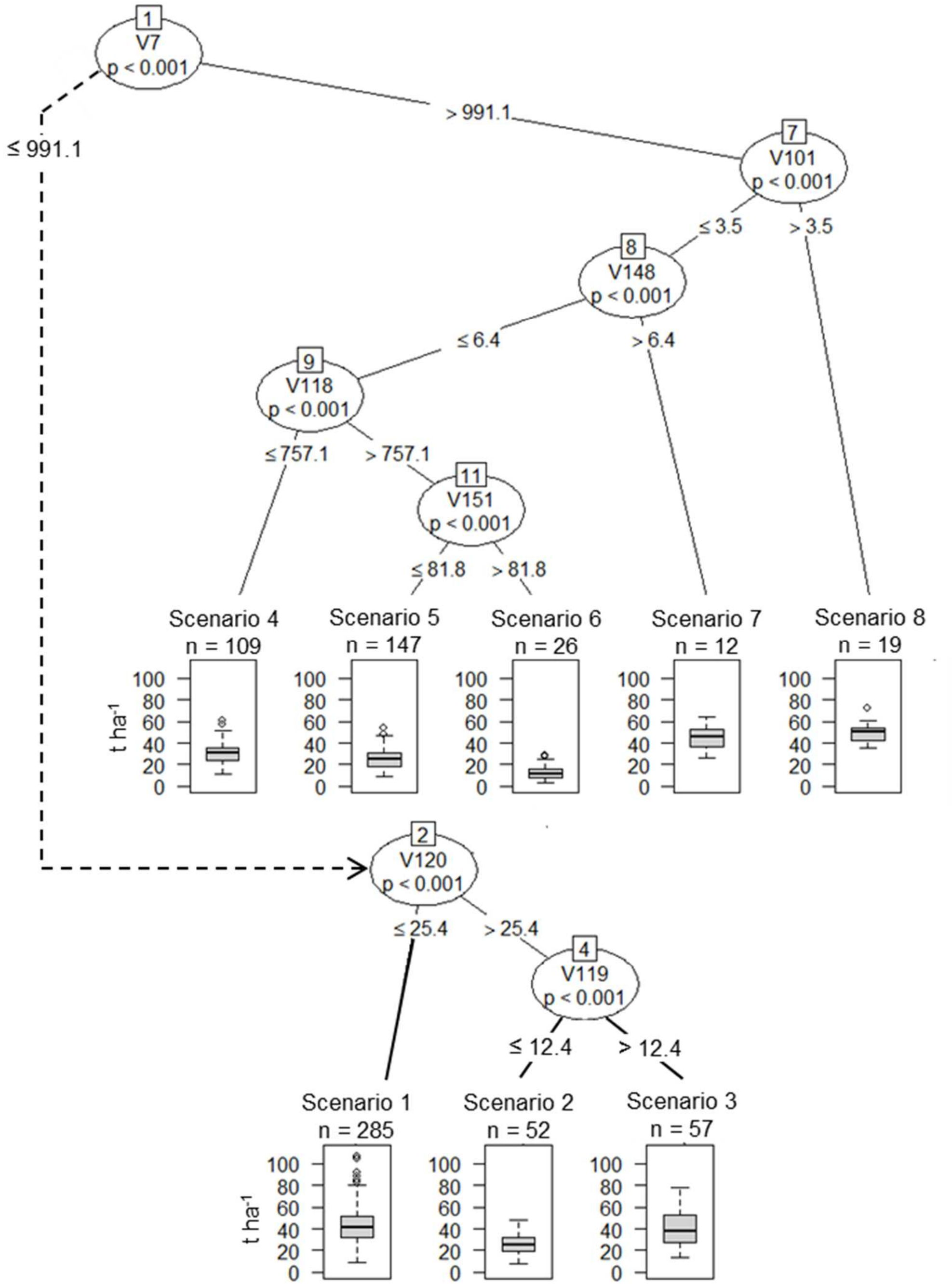


FIG. 3.6: Influence of climate variation on inter-year total yield variation for the early planting window*

However, the coefficient of variation was ~ 30% for both scenarios, which indicated that total yield variation was caused by additional climate or non-climate variable interactions not detected by CART analysis.

Climate events related to atmospheric pressure dominated high quality yield scenarios for the early planting time (Fig. 3.7).



Vertical axes represent high quality yields. Key: V7 (P0 maximum atmospheric pressure, mbar); V101 (P3 average rainfall, mm); V118 (P4 maximum solar radiation, watt m^{-2}); V119 (P4 minimum low wind chill, °C); V120 (P4 maximum wind chill, °C); V148 (P5 average wind speed, km h^{-1}); V151 (P5 maximum relative humidity, %); all splits and levels are shown.

FIG. 3.7: Influence of climate variables within the early planting window on high quality tomato yield as identified by CART analysis

Low atmospheric pressure (< 991.1 mbar) during the early crop development stages (P0) was associated statistically with improved high quality yield outcomes (see first split in Fig. 3.7) and was a useful indicator for explaining inter-year variation in high-quality yield (Fig. 3.8).

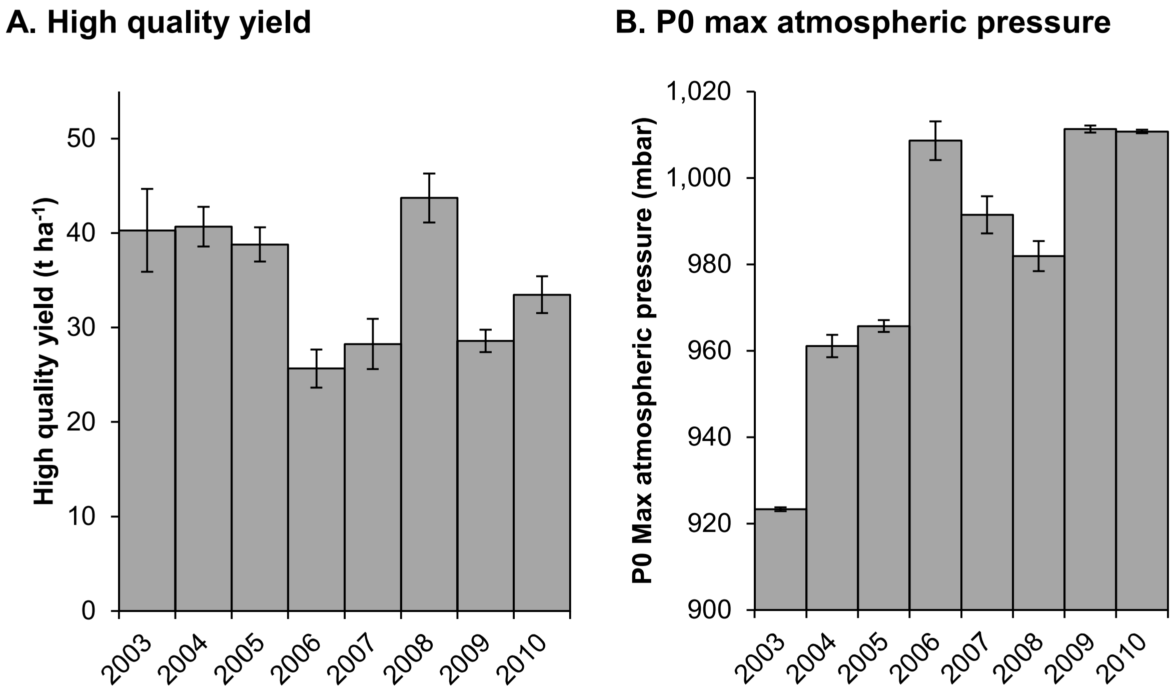
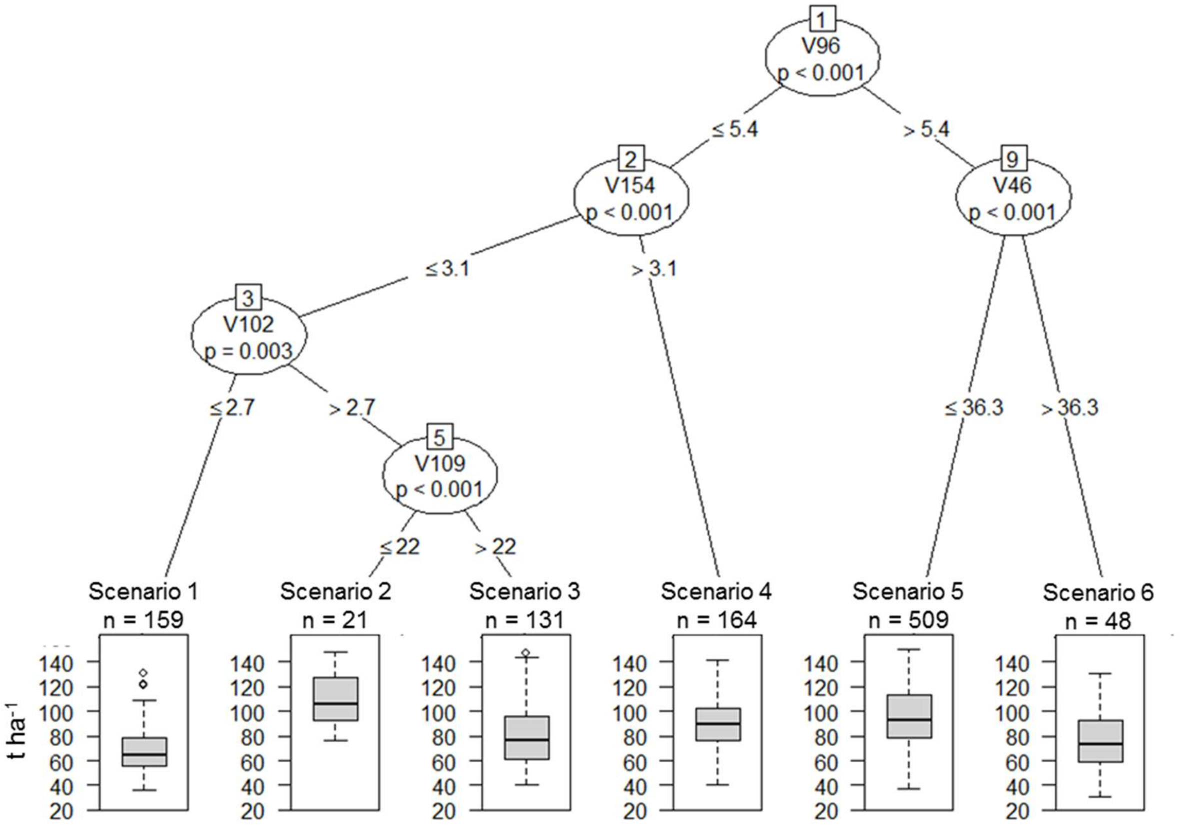


FIG. 3.8: Inter-year variation in high quality tomato yield (A) as influenced by atmospheric pressure during the early planting time (B)

However, this advantage was lost when cold conditions (e.g., average minimum wind chill temperature <12°C) prevailed during the later harvest periods (scenario 2, Fig. 3.7). High average rainfall characterized the early planting window, but the quantity was not a direct cause of high quality yield problems. The absence of desiccating winds (< 6.4 km h^{-1}) when high humidity conditons prevailed during the later development stages were characteristic of the worst high quality yield scenario (scenario 6, Fig. 3.7).

3.3.3 Optimum planting time

Differentiation between low and high total yield during the optimum planting time was statistically attributed to five climate variables in six scenarios (Fig. 3.9). For the optimum planting time, in 49.3% of instances, high total yields (average of 95.1 t ha^{-1}) were obtained when humidity was low (<36.3%) during the first five weeks after planting and high average wind speeds prevailed later in the growth season (scenario 5, Fig. 3.9).



Vertical axes represent total yield. Key: V46 (P1 low humidity, %); V96 (P3 average wind speed, km h^{-1}); V102 (P3 atmospheric evaporative demand, mm d^{-1}); V109 (P4 average temperature, ^{o}C); V154 (P5 atmospheric evaporative demand, mm d^{-1}); only the first four levels are shown.

FIG. 3.9: Influence of climate variables within the optimum planting window on total yield as identified by CART analysis

This represented the dominant yield and climate combination in the optimum planting window. In 15.9% of instances, average yield of 89.5 t ha^{-1} was recorded when the average wind speed was <5.4 km h^{-1} during the first five weeks of harvest but average daily atmospheric evaporative demand exceeded 3.1 mm d^{-1} during the final harvest period (scenario 4, Fig. 3.9). The worst yield scenario occured in 15.4% of instances (average of 79.6 t ha^{-1}); low wind speed and low evaporative demand during the first and final harvest periods characterized this low-yield scenario (scenario 1, Fig. 3.9). The best yield scenario (average of 108.2 t ha^{-1}) involved a combination of ideal climate conditions during key crop development stages: high (but not excessive) average atmospheric evaporative demand (>2.7 but <3.1 mm d^{-1}), average temperature <22^{o}C and average wind speed of <5.1 km h^{-1} (scenario 2, Fig. 3.9). However this scenario occurred only 21 times (2.0%) during the eight-year study period.

The low total yield in 2007 was attributed mainly to insufficient atmopsheric evaporative demand during the first harvest period of the optimum planting window (Fig. 3.10).

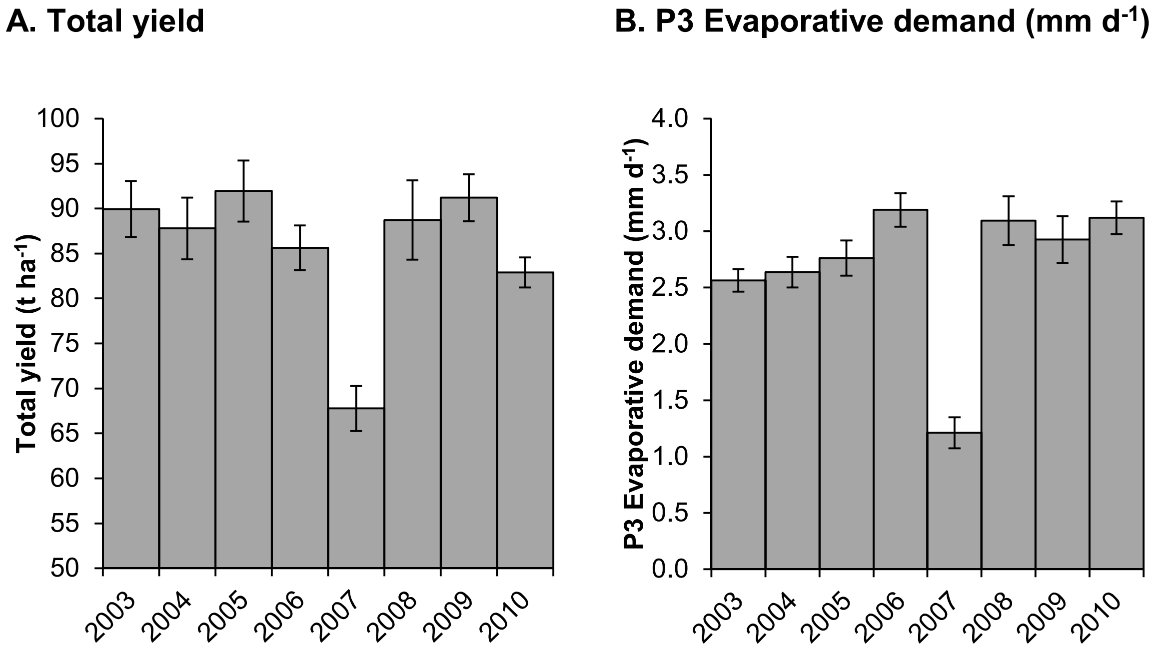
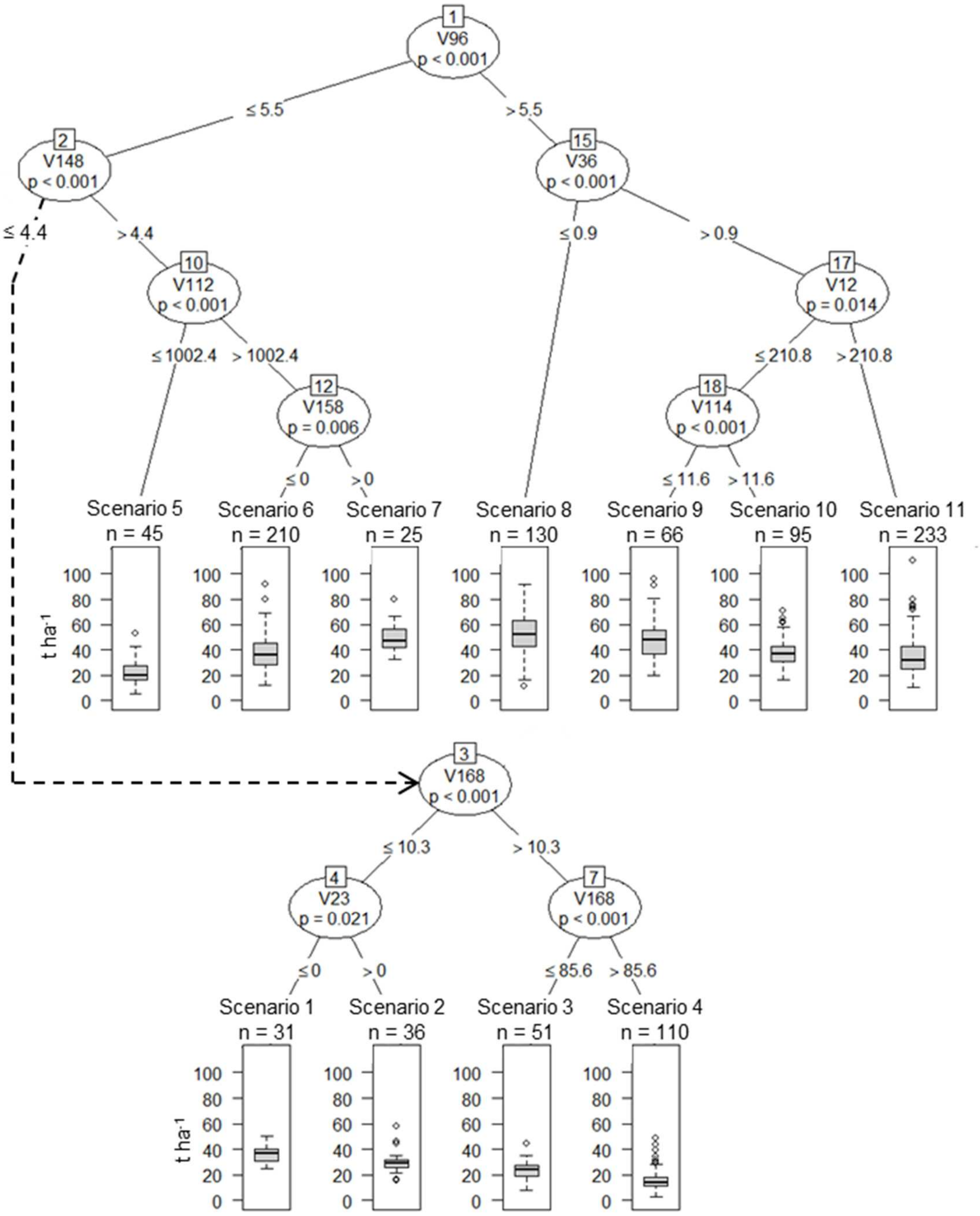


FIG. 3.10: Inter-year variation in tomato yield (A) as influenced by the atmospheric evaporative demand during the first harvest period (B) during the optimum planting window

Tomato quality was influenced in most scenarios by wind speed during the first and last harvest periods (Fig. 3.11). Without the benefit of desiccating winds, rainfall had a strong negative impact on tomato quality and featured prominently in the lowest quality scenarios (scenarios 2-4, Fig. 3.11). An average low dew point of <0.9ºC characterized the best high quality yield scenario (scenario 8, Fig. 3.11). Also indicated is that non-damaging cold temperature exposure was an important aspect of open field fresh-market tomato quality (e.g. scenario 7, Fig. 3.11).



Vertical axes represent total yield. Key: V12 (P0 average maximum solar radiation, watt m^{-2}), V23 (P0 rain, mm), V36 (P1 minimum dewpoint, °C), V96 (P3 average windspeed, km h^{-1}), V112 (P4 minimum atmospheric pressure, mbar), V114 (P4 minumum dewpoint, °C), V148 (P5 average windspeed, km h^{-1}), V158 (P5 cold units, GDD), V168 (cumulative rainfall 15 weeks after planting, mm); all splits and levels are shown.

FIG. 3.11: Influence of climate variables within the optimum planting window on high quality tomato yield as identified by CART analysis

A peculiar aspect of these results was the association of climate variation before planting (phase P0) with variation in the final tomato quality profile, e.g., solar radiation and rainfall (scenarios 9-11 and 1-2 respectively, Fig. 3.11). The practical influence of rain on quality can be attributed to disease-conducive conditions or co-correlation with other climate variables not detected by CART analysis. However, the role of solar radiation levels before planting and the eventual final tomato quality yield is difficult to explain.

From an inter-year perspective, completely different climate variables influenced high quality yields in 2006 and 2008, such as low wind activity during the first five-week harvest period (Fig. 3.12).

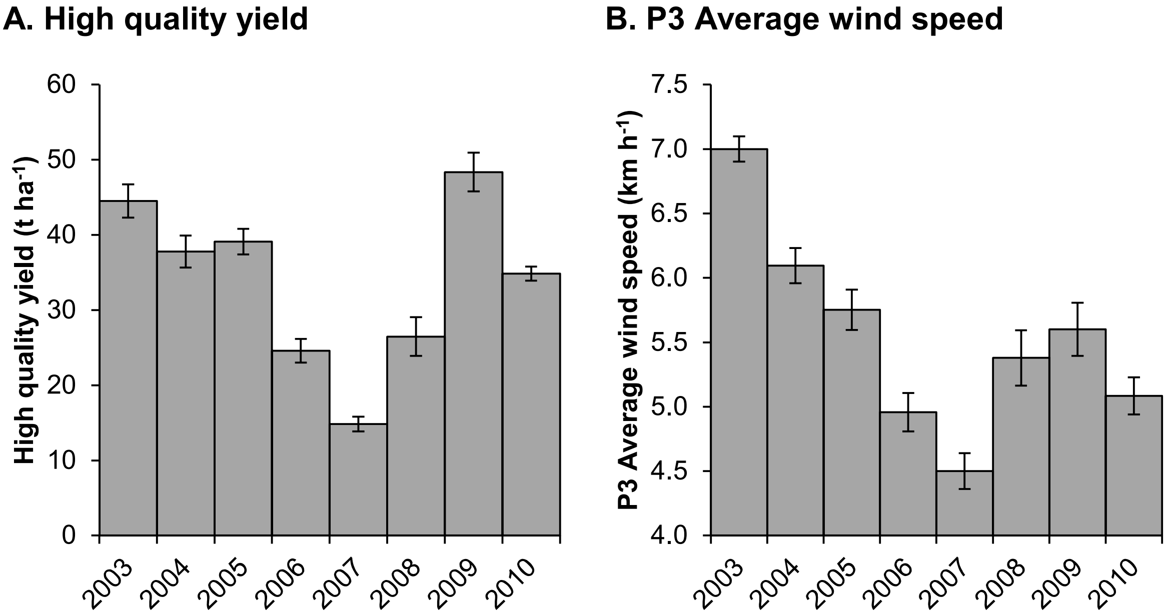


FIG. 3.12: Inter-year variation in tomato quality (A) as influenced by average wind speed during the first harvest period (B) for the optimum planting window

This, together with the onset of above-average rainfall towards the latter part of the planting window (Table 3.3), explained partially the low quality yield observed in 2007 as well.

TABLE 3.3: Occurrence of rainfall within the first five weeks after planting during the optimum planting window for 2003 to 2010[a]

Planting	**Year**							
week	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
20	260%	130%	65%	65%	65%	0%	130%	0%
21	260%	0%	0%	0%	130%	520%	130%	0%
22	325%	65%	0%	0%	130%	520%	130%	130%
23	325%	65%	0%	0%	130%	520%	195%	130%
24	195%	65%	0%	0%	130%	520%	195%	130%
25	65%	65%	0%	0%	130%	520%	65%	195%
26	65%	65%	0%	0%	65%	130%	65%	195%
27	0%	0%	0%	0%	65%	130%	65%	65%
28	0%	0%	0%	0%	65%	130%	0%	65%
29	0%	0%	0%	0%	0%	130%	0%	65%
30	0%	0%	0%	0%	0%	130%	0%	0%
31	0%	0%	0%	0%	0%	65%	0%	0%
32	0%	65%	0%	0%	0%	65%	0%	0%
33	65%	65%	0%	0%	0%	0%	0%	0%
34	65%	65%	0%	0%	0%	0%	0%	0%
35	65%	65%	0%	0%	195%	0%	65%	0%
36	65%	65%	0%	0%	1559%	0%	65%	0%
37	65%	0%	0%	0%	1624%	0%	65%	0%
38	195%	325%	0%	325%	1624%	130%	65%	0%

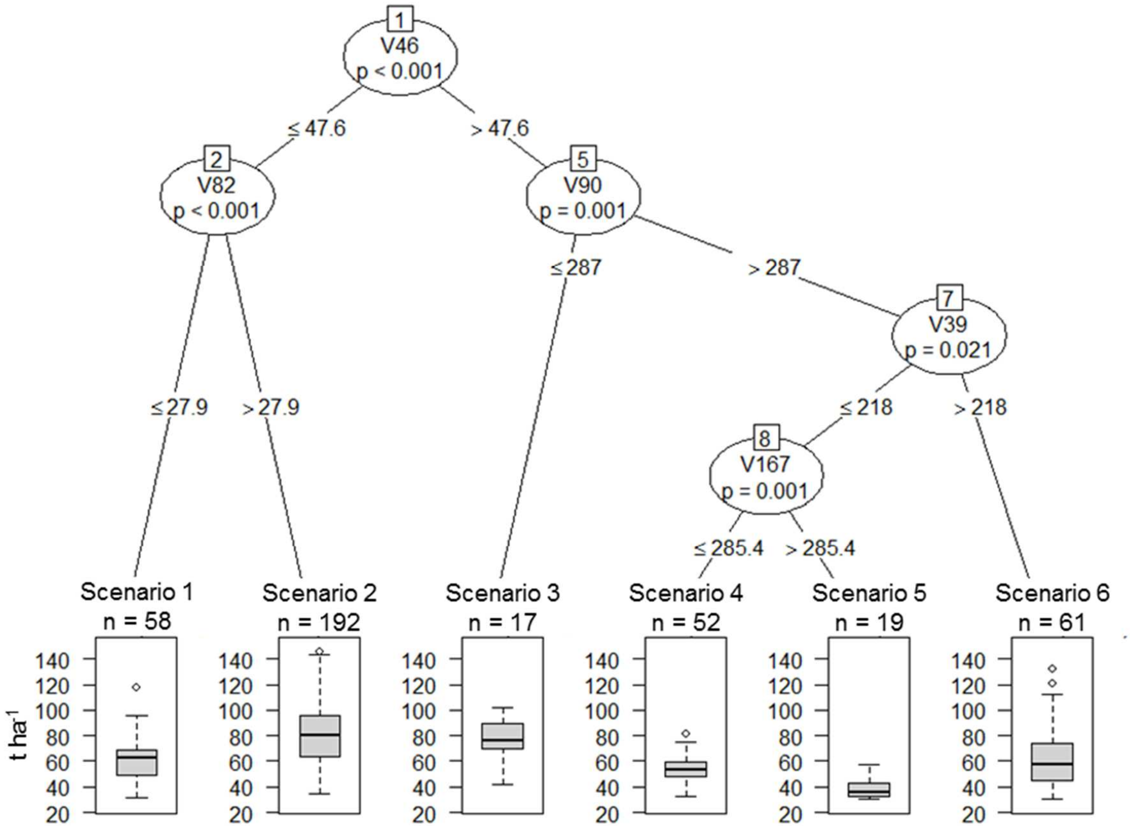
[a] Rainfall is expressed as a percentage of the table grand mean; colour intensifies from green to red show the magnitude of the deviation from the grand mean of the table

In the optimum planting time, high quality yield was more sensitive to climate variation than total yield. The coefficient of variation (CV) for total yield scenarios ranged from 19.9% to 29.8%, whilst the range was 24.6% to 45.2% for high quality yield scenarios.

An important limitation of this study is that five-week climate summaries are not sensitive enough to gauge tomato quality which is affected by hour-to-hour and day-to-day differences in climate. Another plausible explanation involves management responses to different climate-related challenges.

3.3.4 Late planting time

Differentiation between low and high total yield during the late planting time was attributed statistically to five climate variables in six scenarios (Fig. 3.13).



Vertical axes represent total yield. Key: V39 (P1 average solar radiation, watt m^{-2}); V46 (P1 minimum relative humidity, %); V82 (P3 maximum temperature, °C); V90 (P3 average maximum solar radiation, watt m^{-2}); V167 (cumulative rainfall 10 weeks after planting, mm); all levels are shown.

FIG. 3.13: Influence of climate variables within the late planting window on tomato total yield as identified by CART analysis

In 48.1% of instances, high total yields (average of 80.9 t ha^{-1}) were obtained when the minimum relative humidity was less than 47.6% during the first five weeks after planting and the maximum temperature during the first harvest period exceeded 27.9°C; T_{max} for this sub-dataset was 31.2°C (scenario 2, Fig. 3.13). This was the dominant yield/climate interaction for the late planting time.

The worst scenario was characterized by climate events during the first five weeks after planting (relative humidity >47.6%, average solar radiation <218 watt m^{-2}), the first harvest period (average high solar radiation >287 watt m^{-2}), and high cumulative rainfall (>285.4 mm) during the first 10 weeks after planting (scenario 5, Fig. 3.13). The CV for each scenario range from 17.9% to 35.4%. Inter-year variation in total yield is attributed to low atmospheric pressure during the first five weeks after planting (Fig. 3.14).

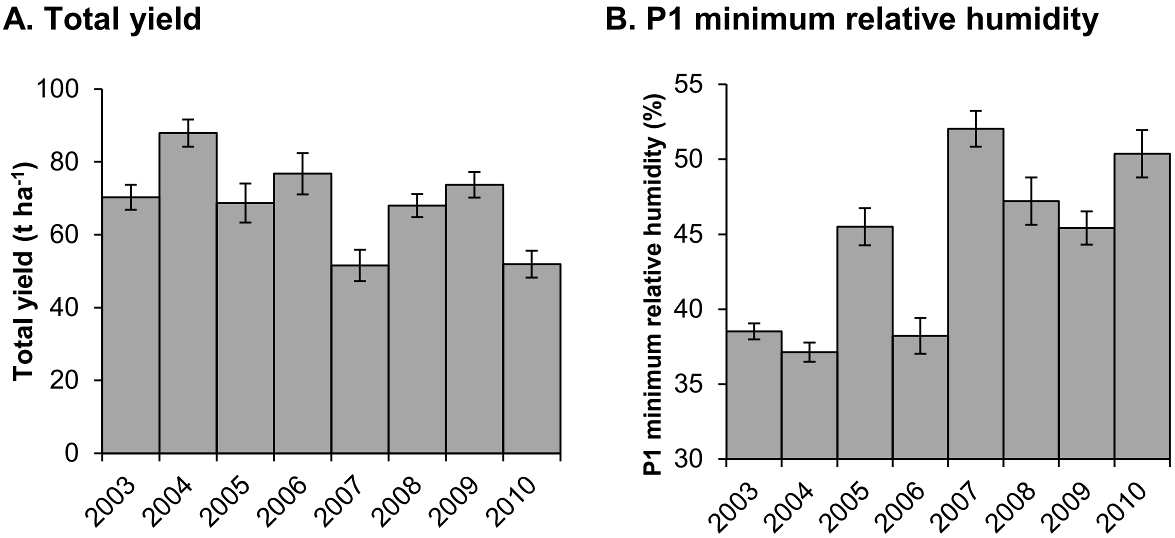
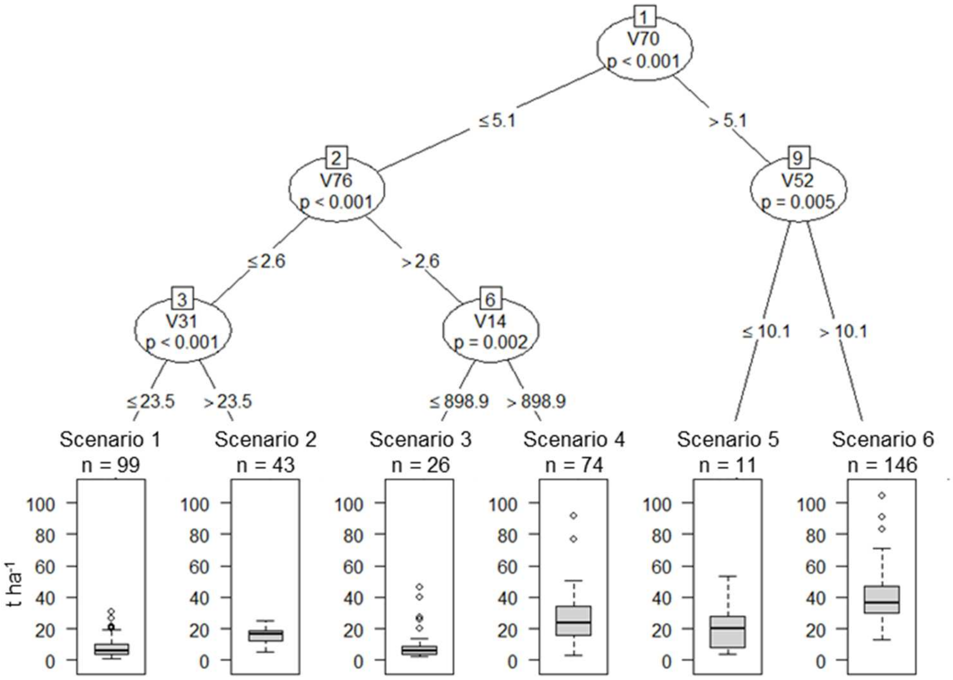


FIG. 3.14: Inter-year variation in tomato yield (A) as influenced by the minimum relative humidity during the first five weeks after planting (B) for the late planting window

High quality yield was affected in the late planting window by five climate variables in six scenarios (Fig. 3.15). In 36.6% of instances, high quality yield was a factor of the ΔT during the first five weeks after planting exceeding 10.1°C and the average wind speed during the initial flowering and fruit set stage being >5.1 km h^{-1} (scenario 6, Fig. 3.15). The worst scenario was observed in 24.8% of instances and was characterized by a low average temperature during the first five weeks after planting, average wind speed of <5.1 km h^{-1} and an evaporative demand <2.6 mm d^{-1} during the initial flowering and fruit set stage (scenario 1, Fig. 3.15). The CV for the scenarios ranged from 28.7% to 110.8%. Inter-year variation in high quality yield was substantial and was attributed to the average wind speed during the initial flowering and fruit set stage (Fig. 3.16).



Vertical axes represent high quality yield. Key: V14 (P0 maximum solar radiation, watt m^{-2}); V31 (P1 average temperature, °C); V52 (P1 ΔT, °C); V70 (P2 average wind speed, km h^{-1}); V76 (P2 evaporative demand, mm d^{-1}); all levels are shown.

FIG. 3.15: Influence of climate variables within the late planting window on high quality tomato yield as identified by CART analysis

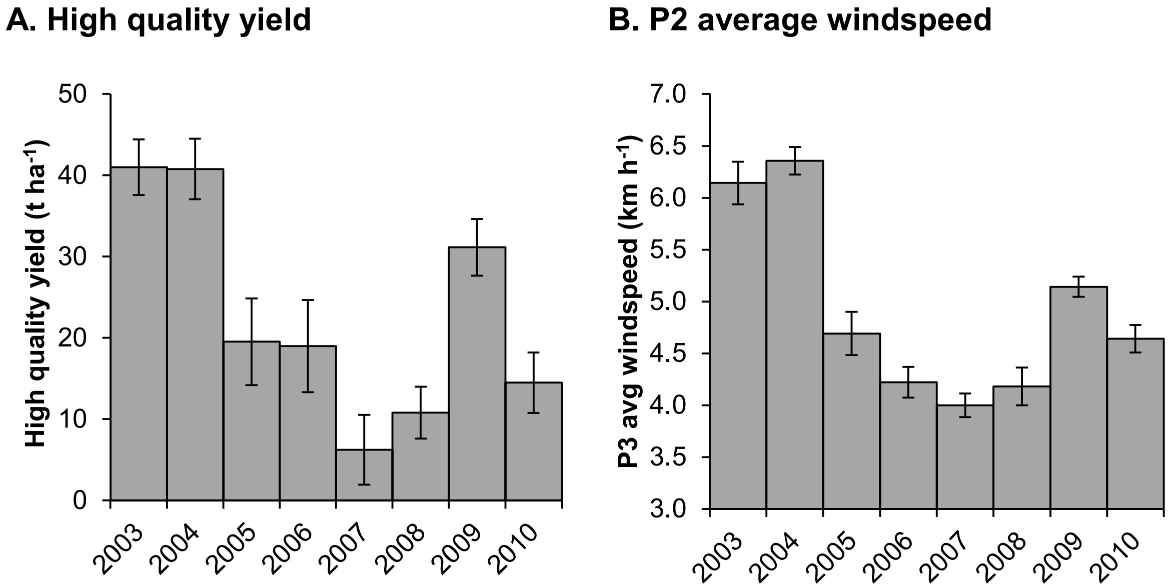


FIG 3.16: Inter-year variation in tomato quality (A) as influenced by the average windspeed during the initial flowering an fruit set stage (B) for the late planting window

3.4 Discussion

3.4.1 Methodology: advantages and disadvantages

Several univariate statistical approaches were used in this study to explore the interaction between tomato yield and climate variables. The correlation matrix of the dataset contained 14 365 combinations. Although several significant correlations were found between climate variables, none of the 168 phenology-based climate variables correlated with tomato yield or quality. This is not surprising given the seasonal and non-linear interactions typical of such datasets. However, when univariate comparisons were made between low (first quartile) and high yield (fourth quartile) scenarios, 160 out of 168 variables differed significantly. This is of limited use given the large number of significant variables potentially influencing tomato yield. Boundary line analysis (BLA) by means of quartile regression is another popular method used to explore yield-limiting factors (e.g., Shatar and McBratney 2004). The successful application of the technique depends on the size of the dataset and the number of bins used. Performing 168 boundary line analyses was deemed impractical for this study because of time constraints and the limited information that could be gained by univariate yield vs variable comparisons (similar to a correlation matrix). In addition, exactly defining the boundaries of the yield-limiting factor is subjective and does not take into consideration interactions with other variables.

To overcome the limitations of univariate statistical methods, two prominent multivariate techniques were used to explore the research question. Principal component analysis is an ordination method useful for comparing user-defined categories or classes based on specific hypotheses. PCA also relies on linear combinations of variables and this is problematic in datasets with time-series characteristics. PCA was used exhaustively to analyse the dataset used in this study. PCA was not useful to clearly define and outline the interactions between yield and climate variables. PCA was able to identify the main climate variables that affected inter-year yield variation. However, it was not possible to identify exactly when a specific climate variable influenced total yield (TY) or HQY and when not. CART analysis is able to bridge the gap between classic BLA and PCA. CART analysis allows for the identification of branching points within the decision tree with statistical precision. The CART diagrams can be used to guide *post-hoc* data analysis and formulate new hypotheses for experimental testing.

Despite the advantages of using CART analysis, users need to be aware of the shortcomings. Earlier CART algorithms were unable to consistently produce classification and regressions trees from the same datasets. The user had to apply additional numerical procedures to improve the reliability of the tree by 'pruning' spurious nodes/branches. This process was subjective and the results remained controversial. Thus, in the early days of its development, statisticians spurned CART analysis. However, recent advances in CART algorithms improved substantially the reliability and objectivity of the process and the final outcome. For example, the introduction of probability-based cut-off controls eliminated the need for pruning the trees, thus restoring much-needed objectivity and statistical accountability to the procedure. Improvements to the CART analysis technique and the availability of an increasing range of CART algorithms and variants has led to a resurgence in the use of CART analysis by the social, medical and the biological sciences (Shepherd et al. 2003, Speybroeck et al. 2004, Orr et al. 2007, Smukler et al. 2008, Tittonell et al. 2008, Ferraro et al. 2009, Zheng et al. 2009, Zhang et al. 2012). Several principles related to tomato yield and quality were corroborated by the CART analysis results reported in this chapter: i) the tomato's sensitivity to temperature extremes (Fig. 3.9, Fig. 3.13), ii) the importance of effective wind pollination (Fig. 3.9, Fig. 3.11, Fig. 3.16), iii) the necessity of adequate evaporative demand (Fig 3.9, Fig. 3.15), iv) the negative impact of high humidity associated with rain or overcast conditions (Fig. 3.11) and v) the importance of desiccating winds (Fig. 3.12, Fig. 3.15).

Although CART analysis is useful to unpack complex datasets and identify potential interactions among the variables, the initial results must not be accepted at face value. For example, it was hard to find plausible biophysical explanations for several of the statistical scenarios produced by the CART analyses described in this chapter (to be discussed in more detail in section 3.4.4):

i) The influence of the average atmospheric pressure five weeks before planting on the final, cumulative tomato yield and quality outcome nearly 25 weeks later during the early (scenarios 1-8, Fig. 3.7) and late (scenarios 3 and 4, Fig. 3.15) planting times;
ii) The association of very low dewpoints (<0.9°C) with high tomato yield (optimum planting time; scenario 8, Fig. 3.11);
iii) The contradictory association of low maximum temperature (<27.9°C) with high total yield outcomes and vice versa when the maximum temperature exceeded 27.9°C (late planting time; scenarios 1 and 2, Fig. 3.13);

iv) The association of low solar radiation (≤287 watt m^{-2}) with above-average total yield outcomes (late planting time; scenario 3, Fig. 3.13).

CART results can be misinterpreted or prematurely rejected by researchers due to a lack of understanding the particular dataset in question or the CART analysis process itself. Since CART analysis may identify a split in the dataset with statistical precision because the P-value is used as cut-off criterion, it is vital to follow-up every branch - especially the terminal node - and look at the raw data associated with the specific statistical scenario. Furthermore, based on personal experience, the reliability of CART results decline with the size of the dataset (e.g., low number of entries). The majority of the problems associated with the CART results of this chapter was associated with the late planting time. Although this dataset was still relatively large (399 entries), the recursive partitioning may have weakened the structure of the dataset, thus reducing the chance of detecting meaningful statistical associations. Furthermore, the late planting time is the worst time of the year to grow tomato crops in the Lowveld region, which means the crop is continually stressed by a range of biotic and abiotic stressors. Hence, the growers' responses to these stressors, in terms of crop management and their ability or inability to reduce crop stress, need to be considered as well.

It is important to acknowledge these inconsistencies with the expected outcome or assumed norm. It is incumbent on the researcher to identify variables previously overlooked that may have led to the particular statistical, yet illogical outcome. To this end, i) the complexity of this thesis (and its underlying hypotheses) was well appreciated from the outset, ii) a lot of time and money were spent on compiling very detailed and complex datasets, and iii) a range of uni- and multivariate statistical procedures were sought out and directed at the complex datasets.

3.4.2 Regional focus

Although climate variation is often studied at the global and national scale, there is good cause for emphasizing regional climate variation studies. Remotely sensed climate datasets provide fairly reliable predictions based on flat topographies but are unreliable where mountainous regions are involved (Van Wart et al. 2013a). The tomato production region studied is located in a valley and represents a micro-climate zone at regional scale, similar to the well-known, but much larger, tomato production regions in the Sacramento and San Joaquin valleys in California.

The influence of ENSO on South African precipitation is difficult to predict, with substantial differences, 50-200% deviance from the mean, reported over the long-term at the regional level (Kane 2009). Indeed, climate prediction even with long-term data in hand, is risky for sub-tropical agriculture given the medium to long-term unpredictability of rain. Thus, greater involvement/integration of theoretical research and field observations are needed to manage uncertainty in these regions at the farm level in a 'bottom up' approach (Matthews et al. 2013, van Ittersum et al. 2013, Köstner et al. 2014).

However, lack of accurate, long-term climate data at the field level is a cause for concern. This is more of a problem for scientists, who rely on long-term datasets, going back >40 years, for reference purposes (Sainju et al. 2001, Rinaldi et al. 2007, Campiglia et al. 2010, Braunack et al. 2012). On the other hand, producers repeatedly bemoan the gross inaccuracy of third-party weather forecasts, especially in rural areas, and think 'it was better to be roughly right than precisely wrong' (from Meinke and Stone 2005). Nevertheless, several years of planting time results must be considered to properly evaluate crop performance based on micro-climate conditions of a specific region (Cuartero and Rodriguez 1994). Consequently, climate studies at the farm-level of focus will have to be conducted differently because of the paucity of data and the non-academic end-user of the results (Jones et al. 2000). In addition, the farmers' wealth of experiential knowledge and observance of crop responses to local climate variability are significant assets. With the above arguments in mind, this study achieved its objective through analysis of climate and yield data supplied by the tomato producers. Research results were communicated to the producers in a 'farmer-friendly' manner, which resulted in positive feedback and changes to the planting programs for this agroecological zone.

3.4.3 The usefulness of climate summaries

The effect of climate variation on tomato yield is not limited to general events that occur during the entire cropping cycle but specific climate events during specific growth stages are likely to influence the crop's cumulative productivity. Stress during the early stage of the tomato production cycle is the dominant cause of yield reduction (May and Gonzales 1994, Rao and Li 2003). On the other hand, damaged young tomato plants can recover completely after severe climatic stress (high wind/rain), but older plants not (Ozores-Hampton et al. 2013). Tomato fruits are larger during the first harvest events but decreases toward the end of the cultivation period (Abdul-Baki et al. 1992). Stress during the late crop development stage has advantages and disadvantages (May and Gonzales 1994), depending on the desired end-result. For example, since tomato prices are very volatile over the short term, irrigation management can be used to hasten fruit ripening for exploitation of favourable market conditions (Karlen et al. 1983, Horchani et al. 2008); in the same way fruit ripening can be delayed to avoid unfavourable market conditions.

Understanding the conditions that promote plant survivorship in the face of extreme climatic distress is necessary for climate-smart agriculture (Niu et al. 2014). This means weather data has to be collected and analysed. Because of the sheer volume of hourly-recorded climate data, researchers approach this dilemma by summarizing selected climate variables according to specific periods. The 10-day period is a popular choice (Maršić et al. 2005, Riahi and Hdider 2013), as are monthly or four-weekly summaries (Sainju et al. 2001, Fraisse et al. 2006, Melero et al. 2012). Qiu et al. (2013) used climate averages for the entire cropping cycle. Chassy et al. (2006) focussed only on temperature and solar radiation for the 25-day period preceding the tomato harvest. Still others widen the analysis window by focussing on crop-specific phenological or growth stages. Tomato irrigation is commonly adjusted according to three or four crop development stages (Ngouajio et al. 2007, Wang et al. 2011, Chen et al. 2013, Peillon et al. 2013, Qiu et al. 2013, Zheng et al. 2013):

- the seedling development stage
- the first flowering and fruit set stage
- fruit maturation stage
- harvesting stage

The exact delineation of each stage varies because of the crop’s response to climate variation and should be adjusted according to visual observations (Dodds et al. 1997, Zheng et al. 2013). Therefore, the use of five-week, growth stage-specific climate summaries in this study has merit. However, when a large dataset supplied by a producer is used, it is not possible for the researcher to know the exact duration of each growth stage, which means certain assumptions have to be tolerated. The approach to climate summaries used in this study provides a valuable tool for use in future research where the specific impact of short-term climate variation can be evaluated easily.

3.4.4 The climate differences between planting times

A complex picture emerges from this study regarding the interactions between climate variables and tomato yield/quality. Different sets of climate variables influence the final yield and quality outcome for every planting window (Table 3.4). These differences will be discussed in more detail in the following sections.

TABLE 3.4: Summary of the sensitivity of the tomato growth stages to climate variation during the different planting windows[a]

	Tomato production stage					
	P0	**P1**	**P2**	**P3**	**P4**	**P5**
Total yield:						
Early						▨
Optimum				▨		▨
Late		▨				
High quality yield:						
Early	▨				▨	▨
Optimum	▨	▨		▨	▨	▨
Late		▨	▨			

[a] Shaded areas indicate sensitivity to climate variation

3.4.4.1 Temperature differential

The early planting time (from summer to winter), exposes the seedling to high temperatures and the mature plant to gradually decreasing temperatures during the harvest season. On the other hand, the late planting time (from spring to summer), exposes the seedling to cool temperatures which rapidly increase to the maximum summer temperatures of ~30°C. Therefore, different planting times expose different growth stages to potential yield-limiting high temperatures. However, every growth and development stage of the tomato plant is sensitive to temperature stress and this plays a key role in explaining yield variation within each planting window.

For the early planting time, the results show that total yield is sensitive to the temperature differential (ΔT, see formula 3.2 in section 3.2.3) between day and night temperatures in the final five weeks of harvest (Fig. 3.6). For the late planting time, the difference between high and low quality yield hinges on a ΔT of 10.1°C during the seedling stage (scenarios 5 and 6, Fig. 3.15). Although temperature dominates as yield-influencing climate variable, the ΔT value is an important yield-influencing temperature variable in specific circumstances only (Rudich 1984). The ΔT value itself is not useful in isolation and has to be interpreted with the actual maximum and minimum temperature ranges. For example, high day/night temperatures (e.g., 30/20°C, ΔT = 10°C) are associated with reduced fruit set (Rudich 1984), whereas night temperatures < 22°C achieve the opposite (Willits and Peet 1998). Thus, when either the actual minimum or maximum temperatures already exceed critical limits, the ΔT value is of limited use. For example, low (<10-13°C) or high (>30°C) temperatures negatively affect pollen viability and fruit set (Charles and Harris 1972, Levy et al. 1978, El-Abd and El-Beltagy 1996, Adams et al. 2001, Lobell et al. 2007). The ΔT value becomes useful during the onset of colder temperatures at the approach of winter when the nights are cooler yet the days remain warm (ΔT >14.5°C). Thus, the colder conditions arrest activity of pests and diseases during the night (whose activities affect the visual appearance of the fruits), but the warm day temperatures allow vegetative growth (late planting time) and fruit development (early planting time) to continue unabated. The possible role of a temperature difference of 8-10°C between maximum and minimum temperatures in protecting against the effects of excessive light exposure was noted by several research groups (Matsuda et al. 2012, Sysoeva et al. 2012, Velez-Ramirez et al. 2012).

The benefits of cooler production temperatures on total yield and quality of tomato has been reported (Zotarelli et al. 2009), as well as the use of chilling hours to calculate the extent of exposure to yield-limiting cold conditions (Elizondo and Oyanedel 2010). Favati et al. (2009) adjusted irrigation scheduling in accordance with the prevailing evaporative demand, but average annual total yield still varied by 45%. Although the seasonal average temperatures did not differ substantially in their study, closer inspection of daily temperature profiles revealed maximum temperatures during the early growth stages of <30°C for the good year and >30°C for the bad year; the minimum temperatures were <15°C in a good year, and >15°C in the bad year. Fruit ripening rates are substantially lower when tomatoes are grown at constantly low temperatures of <18°C (Adams et al. 2001). However, frost or continuous exposure of tomato plants to yield-limiting cold temperatures is not common in the Lowveld production region. The accumulation of cold units appears to explain the decrease in total yield and quality commonly experienced from PW15-19 (Fig. 3.1 - 3.3). This observation is supported by the negative association of cooler wind chill conditions with tomato quality (<12.4°C, scenario 2,

Fig. 3.7). Thus, the combination of cumulative cold units, in conjunction with daytime temperature variation (ΔT), negatively influences the tomato yield and quality in the early (P5 stage) and late (P1 stage) planting time.

3.4.4.2 Heat, solar radiation, and evaporative demand

Tomato quality is sensitive to water deficit brought about by interactions between temperature, solar radiation and atmospheric pressure (Islam and Khan 2000, Bojacá et al. 2009, Marcelis et al. 2009, Teng et al. 2012, Flexas et al. 2013). In the Lowveld bioregion, these interactions were associated statistically with variations in tomato yield in the late planting time and tomato quality in all three planting times.

The flowering and fruit set stage is sensitive to temperature stress (Rudich 1984, El-Abd et al. 1996, Elizondo and Oyanedel 2010). After fruit set, fruit size is influenced by assimilate supply which is dependent on solar radiation (Ho 1996). Sufficient nitrogen increases leaf area index (LAI) and thus the absorption of PAR (Tei et al. 2002), which in turn allows the plant to develop and grow due to the availability of photosynthate, the building blocks of the plant (Ho 1996). Cumulative intercepted radiation correlates with tomato fruit weight (Scholberg et al. 2000). However, excessive PAR (> 1000 μmol m^{-2} s^{-1}) limits photosynthetic processes (Matsuda et al. 2012, O'Carrigan et al. 2014) and eventually leads to yield reduction (Rudich 1984). High temperatures (24-35ºC) reduce pollen viability (El-Abd and El-Beltagy 1996), while excessive temperatures (>38ºC) lead to flower drop and reduce fruit set (Levy et al. 1978). The fruit maturation stage is also sensitive to temperature stress (Adams et al. 2001, Montemurro et al. 2009). The main problems are reduced fruit growth rate (Thompson et al. 1999, Diaz-Perez et al. 2007), fruit discolouration (Bierlen and Grunewald 1995), and increased expression of nematode and virus-associated disease symptoms (Zacheo et al. 1995, Diaz-Perez et al. 2007, Verdejo-Lucas et al. 2013). Suboptimal temperatures (12-15ºC) limit root growth (Venema et al. 2008), nutrient uptake (Gent 1992) and general crop development rate (Ntatsi et al. 2014).

Atmospheric pressure is an important driver of seasonal weather variation. Low atmospheric pressure conditions are associated with rainfall and higher relative humidity; these factors are associated with yield and quality decline in tomatoes (Lipton 1970, Bakker 1990, Holder and Cockshull 1990, Colla et al. 2000, Hanson et al. 2000). CART analysis corroborated the negative impact of rainfall and humidity on tomato yield and quality during the optimum and late planting times (discussed in sections 3.4.4.3 and 3.4.4.5). Yet, CART analysis indicated that tomato quality during the early planting time was affected positively by lower (≤ 991.1 mbar) atmospheric pressure in the P0 stage (five weeks before planting). How can the higher yields at low atmospheric conditions be explained when the opposite effect was expected? Although rainfall occurs during the early planting time (Fig. 3.2A), the frequency is highly variable and the actual quantities decline towards the onset of fall and winter. Thus, even though low atmospheric pressure conditions occurred in 56% of the scenarios, humidity and rainfall were not associated with variation in tomato quality (as opposed to scenario 6, Fig. 3.7). The early planting time initially subjects the seedling to high temperature stress (also observed by Tanaskovik et al. 2011). Overcast conditions at the start of the early planting time, limited seedling exposure to harmful levels of photosynthetically active radiation (PAR) while possibly trapping some of the radiation heat (especially at night) that allowed crop growth and development to continue despite the steady onset of cooler conditions. Atmospheric pressure was an important component of the first rudimentary wheat yield prediction models (Steyaert et al. 1978, Michaels 1982). Thus, the lower atmospheric conditions may not have directly influenced tomato growth and development, but it was a leading indicator of the medium-term climate conditions in the Lowveld tomato production region.

Effective evapotranspiration is a crucial component of successful tomato production. The cumulative evaporative demand values calculated for the Lowveld tomato production region are similar to other tomato production regions in the world: 556-638 mm (South Serbia; Aksic et al 2011), 528-758 mm (California, Hanson and May 2006), and 290-498 mm (South Italy, Katerji et al. 2013). The maximum irrigation demand occurs during the fruit set stage (Rudich and Luchinsky 2012). Evaporation is driven primarily by the prevailing temperatures and is most efficient at higher, but not limiting, maximum temperatures (<35ºC). For this reason, tomato production is successful in the hot and dry climate regions of the world. However, evapotranspiration efficiency declines when high humidity accompanies suitable temperature conditions. For example, during the late planting time (from spring to summer), almost all of the development stages of the tomato plant is exposed to yield-limiting temperature stress (Fig. 3.3A). This climate variable, in conjunction with high relative humidity and high rainfall, explains why tomato yield and quality is consistently dismal in the plate planting period. The efficiency of the producer’s response to these temperature-related challenges, i.e., adjustment of irrigation scheduling, is another factor that compound the complexity of the dilemma.

3.4.4.3 Relative humidity and dew point

The relative humidity and the dew point are climate variables that relate to the moisture content of the atmosphere: the higher the relative humidity or dewpoint, the higher the moisture content of the air. Although the latter term is preferred by agri-climatologists, the term ‘relative humidity’ is encountered regularly in the scientific and commercial literature. The moisture content of the air in the cropping environment is an important variable for explaining variation in tomato yield and quality, and featured prominently in several of the statistical scenarios identified by CART analysis.

High humidity was associated with summer rainfall and low atmospheric pressure (increased cloud cover) in the Lowveld tomato production region. High relative humidity (>81.8%) was associated with reduced quality in the early planting time (scenario 6, Fig. 3.7). High dew points were associated with lower total yields in the optimum planting time (scenario 10, Fig. 3.11). High humidity causes yield reduction due to poor fruit set and small fruit size (Lipton 1970, Bakker 1990, Holder and Cockshull 1990). The physical appearance (size and shape) and nutritional quality of the tomato fruit decreases at high humidity (Bakker 1990, Holder and Cockshull 1990, Xu et al. 2007). Sensitivity to high humidity and high temperatures is highest during the flowering and fruit set stage (Peet et al. 2002). High humidity influences the vapour pressure in the atmosphere, reduces leaf conductance and moisture loss, thus reducing the need for water from the roots. Therefore, when conditions of high humidity and evapotranspoiration coincide, incorrect irrigation can incur avoidable water stress because fertilizers and most pesticides are supplied via irrigation. However, the occurrence of desiccating winds can reduce the potentially negative impact of very high humidity, thus allowing evapotranspiration to occur and roots to function in the face of regular water supply.

Very low humidity (<36.3%) was associated with improved total yield during the optimum planting time (scenario 5, Fig. 3.9). Low humidity (<43.3%), in combination with high maximum temperatures (>27.3°C), was associated with high total yield during the late planting time (scenario 2, Fig. 3.13). The interaction between temperature and humidity is important for tomato production in summer rainfall regions. Lipton (1970), found that high humidity reduced quality during summer but not spring. Low humidity presents several benefits to the tomato plant, such as increased leaf photosynthetic capacity (Xu et al. 2007) and reduced risk of foliar disease (Yunis et al. 1980, Baptista et al. 2008). However, excessively low humidity (vapour pressure deficit >2 kPa) reduces fruit growth rate and final yield (Leonardi et al. 2000), and pollen abnormalities increase (Peet et al. 2002).

Very low dew points may indicate the risk of frost formation. For example, during the optimum planting time, very low (<0.9ºC) average dew points were recorded during the first five weeks after planting (scenario 8, Fig. 3.11). Although tomatoes are known to be very sensitive to frost damage, CART analysis indicated a positive effect on total yield. How is this possible? The lowest dewpoint reading for this sub-dataset was -3.3ºC, thus the seedlings of 56% of the cultivation events were exposed to crop-damaging frost-conducive conditions. Artificial wind is used as a means to protect frost-sensitive crops (e.g., Battany 2012), but wind speed was not associated with the higher-than-expected yield outcome and the low dewpoint, neither did the growers use artificial wind in their fields. The tomato growers in South Africa did light small fires along the perimeter of fields prone to frost damage based on their location and topography (e.g., low-lying and near open water sources). It is plausible that additional crop management variables not considered here might explain the counter-intuitive result.

3.4.4.4 Wind

The occurrence of substantial wind activity was associated with increased total yields in the optimum planting time (scenarios 5 and 6, Fig. 3.9) and improved quality in the late planting time (scenarios 5 and 6, Fig. 3.15). The absence of wind activity exacerbated the negative effect of high relative humidity on tomato quality in the early planting time (scenario 6, Fig. 3.7). Suboptimal wind activity was associated with reduced quality in the early and optimum planting times (scenarios 4-6 in Fig. 3.7 and scenarios 1-4 in Fig. 3.11). Wind speed may be associated with reduced tomato yield due to the tomato’s notorious pollination problems. Air blowers facilitate pollination in open field conditions (Hanna 1999) and mechanical vibrators achieve the same objective in protected cultivation systems. These treatments result in increased tomato yields and quality (Hanna 1999).

Very little is known about the benign impacts of wind and wind speed on tomato physiology. For example, a correlation was found between increased wind speed and the calcium content of kiwifruit (Dichio et al. 2007). Desiccating winds increase transpiration and crop water requirements, especially when high temperatures prevail, thus leading to increased nutrient acquisition from the rhizosphere. Such conditions often prevailed during the optimum planting time (scenario 6, Fig. 3.9) and indicate the producers’ irrigation or nutrient management were not sensitive to this yield-limiting combination of climate variables. Indeed, these tomato producers irrigated based on 'gut-feel' and 'experience', but recently (2013) started basing irrigation scheduling on tensiometer and atmospheric evaporative demand data.

The other important benefit of wind activity is desiccation of the canopy when the risk of foliar disease is high. High wind speed, forced aeration, or increased wind access through canopy management and row spacing, reduce foliar disease incidence on tomato (Yunis et al. 1980, Baptista et al. 2008). If tomato growers insist on utilizing the late planting time, they may mitigate the impact of the aforementioned climate risk factors by cultivating fields exposed to variable wind speeds during that specific time of the year.

3.4.4.5 Rainfall

High quality yield in the optimum planting window (scenario 3 and 4 in Fig. 3.11) and total yield in the late planting window were very sensitive to cumulative rainfall during the first 15 and 10 weeks after planting (scenario 5 in Fig. 3.13). In the USA, the majority of crop failures are associated with excess or no rainfall (Fraisse et al. 2006). Excessive or insufficient irrigation creates similar crop stress. The tomato crop is acutely sensitive to water stress, indeterminate cultivars in particular (Dadomo 1994, Colla et al. 2000, Hanson et al. 2000). For this reason, tomato producers rely on ridge tillage to avoid water stress because of rainfall or irrigation (Rao and Li 2003). The negative effects of excess soil moisture are strongly related to the soil clay content because of the improved water holding capacity (Bhattarai et al. 2006). Above-average rainfall reduces tomato yield substantially due to the interference with fruit set (Alvino et al. 1990). The presence of excessive levels of organic matter in soils increase crop susceptibility to water logging stress and is associated with yield reduction in the tomato (El-Beltagy et al. 1986, Argerich et al. 1999). The mechanism is thought to involve increased ethylene secretion, which hastens the onset of fruit ripening (Jackson et al. 1978, El-Beltagy et al. 1986, Hadid et al. 1986).

3.4.4.6 Continental extreme climate events

The interaction between atmospheric pressure, relative humidity and atmospheric evaporative demand is relatively straightforward. For example, in 2006 evaporative demand of >3 mm d^{-1} coincided with atmospheric pressure of >1013 mbar. However, this relationship was not observed in 2007 when the evaporative demand exceeded 4 mm d^{-1} yet the maximum atmospheric pressure never exceeded 1000 mbar. Based on previous years' data, indications were strong that the early planting window of 2007 would have been a very hot period with a very high evaporative demand in January 2007 (Table 3.5).

TABLE 3.5: Interactions between crop development stage-specific atmopsheric evaporative demand, atmospheric pressure and high quality tomato yield[a]

Planting week		HQY (t ha^{-1})	Evaporative demand (mm d^{-1})						Maximum Atmospheric Pressure (mbar)					
			P0	P1	P2	P3	P4	P5	P0	P1	P2	P3	P4	P5
2006	1	9.8	3.1	2.6	1.3	0.7	0.6	0.4	1032.2	1023.1	991.1	996.2	995.5	999.9
	2	8.1	3.0	2.0	1.3	0.7	0.8	0.2	1037.2	1013.4	991.7	996.8	995.9	1001.3
	3	14.5	3.1	1.7	1.1	0.7	0.6	0.2	1041.8	1004.2	992.3	997.8	996.7	1001.0
	4	24.6	3.0	1.6	0.9	0.6	0.6	0.3	1042.0	993.1	993.7	997.9	997.3	999.6
	5	21.4	2.8	1.3	1.0	0.5	0.5	0.4	1034.4	990.7	994.0	998.2	997.7	994.5
	6	25.7	2.6	1.3	0.7	0.6	0.4	0.7	1023.1	991.1	996.2	995.5	999.9	989.7
	7	34.2	2.0	1.3	0.7	0.8	0.2	1.2	1013.4	991.7	996.8	995.9	1001.3	982.2
	8	31.3	1.7	1.1	0.7	0.6	0.2	1.6	1004.2	992.3	997.8	996.7	1001.0	977.0
	9	29.9	1.6	0.9	0.6	0.6	0.3	2.1	993.1	993.7	997.9	997.3	999.6	973.5
	10	39.5	1.3	1.0	0.5	0.5	0.4	2.2	990.7	994.0	998.2	997.7	994.5	973.9
	11	42.6	1.3	0.7	0.6	0.4	0.7	2.5	991.1	996.2	995.5	999.9	989.7	973.8
	12	27.5	1.3	0.7	0.8	0.2	1.2	2.4	991.7	996.8	995.9	1001.3	982.2	975.7
	13	32.6	1.1	0.7	0.6	0.2	1.6	2.7	992.3	997.8	996.7	1001.0	977.0	974.8
	14	24.8	0.9	0.6	0.6	0.3	2.1	2.9	993.7	997.9	997.3	999.6	973.5	974.9
	15	22.4	1.0	0.5	0.5	0.4	2.2	3.4	994.0	998.2	997.7	994.5	973.9	973.8
	16	22.4	0.7	0.6	0.4	0.7	2.5	3.6	996.2	995.5	999.9	989.7	973.8	972.6
	17	26.6	0.7	0.8	0.2	1.2	2.4	3.9	996.8	995.9	1001.3	982.2	975.7	971.8
	18	23.3	0.7	0.6	0.2	1.6	2.7	3.8	997.8	996.7	1001.0	977.0	974.8	971.5
	19	26.6	0.6	0.6	0.3	2.1	2.9	3.9	997.9	997.3	999.6	973.5	974.9	970.5
2007	1	27.8	4.2	3.9	2.9	2.1	1.3	0.7	965.9	973.6	1003.3	1008.8	1012.8	1015.9
	2	41.3	4.3	3.6	2.7	2.0	1.2	0.7	966.2	980.5	1003.6	1010.4	1013.4	1016.3
	3	33.6	4.1	3.3	2.6	1.8	1.1	0.7	966.3	987.8	1004.2	1012.2	1013.6	1016.8
	4	28.6	3.9	3.3	2.5	1.6	1.0	0.6	965.5	995.2	1005.6	1012.6	1014.0	1017.3
	5	43.2	3.9	2.9	2.4	1.5	0.8	0.6	966.0	1002.6	1007.2	1012.7	1015.1	1016.7
	6	36.2	3.9	2.9	2.1	1.3	0.7	0.7	973.6	1003.3	1008.8	1012.8	1015.9	1016.2
	7	38.0	3.6	2.7	2.0	1.2	0.7	0.8	980.5	1003.6	1010.4	1013.4	1016.3	1015.6
	8	45.3	3.3	2.6	1.8	1.1	0.7	1.2	987.8	1004.2	1012.2	1013.6	1016.8	1014.5
	9	47.5	3.3	2.5	1.6	1.0	0.6	1.6	995.2	1005.6	1012.6	1014.0	1017.3	1013.5
	10	34.7	2.9	2.4	1.5	0.8	0.6	1.5	1002.6	1007.2	1012.7	1015.1	1016.7	1015.7
	11	19.9	2.9	2.1	1.3	0.7	0.7	1.3	1003.3	1008.8	1012.8	1015.9	1016.2	1016.5
	12	19.3	2.7	2.0	1.2	0.7	0.8	1.0	1003.6	1010.4	1013.4	1016.3	1015.6	1017.5
	13	20.6	2.6	1.8	1.1	0.7	1.2	0.9	1004.2	1012.2	1013.6	1016.8	1014.5	1009.6
	14	27.3	2.5	1.6	1.0	0.6	1.6	0.8	1005.6	1012.6	1014.0	1017.3	1013.5	1002.0
	15	12.1	2.4	1.5	0.8	0.6	1.5	0.9	1007.2	1012.7	1015.1	1016.7	1015.7	991.8
	16	17.8	2.1	1.3	0.7	0.7	1.3	1.1	1008.8	1012.8	1015.9	1016.2	1016.5	982.2
	17	14.4	2.0	1.2	0.7	0.8	1.0	1.3	1010.4	1013.4	1016.3	1015.6	1017.5	973.1
	18	14.7	1.8	1.1	0.7	1.2	0.9	1.2	1012.2	1013.6	1016.8	1014.5	1009.6	973.4
	19	14.7	1.6	1.0	0.6	1.6	0.8	1.1	1012.6	1014.0	1017.3	1013.5	1002.0	973.7
2008	1	26.3	1.3	1.5	1.4	1.4	1.5	0.2	968.7	969.1	982.6	1002.0	1015.6	1019.5
	2	30.4	1.6	1.3	1.4	1.5	1.2	0.2	967.7	972.3	982.0	1008.5	1016.9	1020.2
	3	31.1	1.6	1.4	1.3	1.8	0.8	0.4	967.8	974.6	984.0	1014.0	1016.9	1019.7
	4	45.7	1.6	1.4	1.3	1.5	0.8	0.6	968.2	978.0	989.5	1014.5	1017.3	1020.0
	5	42.8	1.5	1.4	1.5	1.7	0.4	0.6	967.8	981.1	995.8	1014.3	1019.3	1020.3
	6	42.8	1.5	1.4	1.4	1.5	0.2	0.6	969.1	982.6	1002.0	1015.6	1019.5	1020.7
	7	42.6	1.3	1.4	1.5	1.2	0.2	1.1	972.3	982.0	1008.5	1016.9	1020.2	1019.9
	8	38.4	1.4	1.3	1.8	0.8	0.4	1.3	974.6	984.0	1014.0	1016.9	1019.7	1020.8
	9	59.8	1.4	1.3	1.5	0.8	0.6	1.7	978.0	989.5	1014.5	1017.3	1020.0	1020.1
	10	61.9	1.4	1.5	1.7	0.4	0.6	2.1	981.1	995.8	1014.3	1019.3	1020.3	1018.6
	11	40.5	1.4	1.4	1.5	0.2	0.6	2.7	982.6	1002.0	1015.6	1019.5	1020.7	1015.9
	12	61.1	1.4	1.5	1.2	0.2	1.1	2.9	982.0	1008.5	1016.9	1020.2	1019.9	1016.0
	13	48.6	1.3	1.8	0.8	0.4	1.3	3.0	984.0	1014.0	1016.9	1019.7	1020.8	1015.6
	14	55.9	1.3	1.5	0.8	0.6	1.7	2.9	989.5	1014.5	1017.3	1020.0	1020.1	1015.1
	15	43.0	1.5	1.7	0.4	0.6	2.1	3.1	995.8	1014.3	1019.3	1020.3	1018.6	1013.8
	16	42.4	1.4	1.5	0.2	0.6	2.7	3.1	1002.0	1015.6	1019.5	1020.7	1015.9	1014.6
	17	47.2	1.5	1.2	0.2	1.1	2.9	3.2	1008.5	1016.9	1020.2	1019.9	1016.0	1014.3
	19	26.7	1.5	0.8	0.6	1.7	2.9	3.3	1014.5	1017.3	1020.0	1020.1	1015.1	1013.7
2009	1	24.9	3.3	2.3	2.5	2.8	1.7	1.0	1009.0	1007.0	1012.5	1014.8	1017.1	1019
	2	25.4	2.5	2.2	2.3	2.8	1.5	1.3	1008.4	1008.4	1012.7	1015.9	1017.6	1018.4
	3	28.7	2.8	2.0	2.3	2.7	1.5	1.0	1007.3	1009.5	1012.6	1017.4	1016.8	1021.4
	4	25.6	2.2	2.5	2.4	2.3	1.4	0.6	1006.7	1010.2	1013.4	1017.2	1017.5	1022.8
	5	22.8	2.1	2.1	2.9	2.0	1.2	0.8	1006.6	1011.3	1014.2	1017.0	1018.7	1023.4
	6	25.2	2.3	2.5	2.8	1.7	1.0	0.8	1007.0	1012.5	1014.8	1017.1	1019.0	1024.7
	7	31.2	2.2	2.3	2.8	1.5	1.3	0.6	1008.4	1012.7	1015.9	1017.6	1018.4	1025.3
	8	32.6	2.0	2.3	2.7	1.5	1.0	1.0	1009.5	1012.6	1017.4	1016.8	1021.4	1023.7
	9	37.2	2.5	2.4	2.3	1.4	0.6	1.4	1010.2	1013.4	1017.2	1017.5	1022.8	1023.0
	10	28.2	2.1	2.9	2.0	1.2	0.8	1.6	1011.3	1014.2	1017.0	1018.7	1023.4	1022.1
	11	32.2	2.5	2.8	1.7	1.0	0.8	1.9	1012.5	1014.8	1017.1	1019.0	1024.7	1021.7
	12	20.7	2.3	2.8	1.5	1.3	0.6	2.7	1012.7	1015.9	1017.6	1018.4	1025.3	1021.3
	13	26.1	2.3	2.7	1.5	1.0	1.0	2.9	1012.6	1017.4	1016.8	1021.4	1023.7	1020.6
	14	32.9	2.4	2.3	1.4	0.6	1.4	3.2	1013.4	1017.2	1017.5	1022.8	1023.0	1019.4
	15	27.2	2.9	2.0	1.2	0.8	1.6	3.2	1014.2	1017.0	1018.7	1023.4	1022.1	1018.1
	16	34.5	2.8	1.7	1.0	0.8	1.9	2.8	1014.8	1017.1	1019.0	1024.7	1021.7	1017.1
	17	19.3	2.8	1.5	1.3	0.6	2.7	2.6	1015.9	1017.6	1018.4	1025.3	1021.3	1015.4
	18	37.1	2.7	1.5	1.0	1.0	2.9	2.8	1017.4	1016.8	1021.4	1023.7	1020.6	1014.1
	19	31.3	2.3	1.4	0.6	1.4	3.2	2.9	1017.2	1017.5	1022.8	1023.0	1019.4	1014.5

[a] Colour scale intensifies from red (low) to green (high) for high quality yield (HQY) and vice versa for the evaporative demand and the atmospheric pressure (red = low and green = high)

These observations point to the unexpected influence of a low pressure cell on the local climate in January and February 2007. Tropical cyclone Favio made landfall in Mozambique on 22 February 2007. This extreme climate event was unusual because it was the first tropical cyclone to pass the southern tip of Madagascar and make landfall in Mozambique during an El Niño year (Klinman and Reason 2008). Satellite images show clouds associated with Favio spread well into South Africa and Zimbabwe on 23 February 2007 (Fig. 3.17).

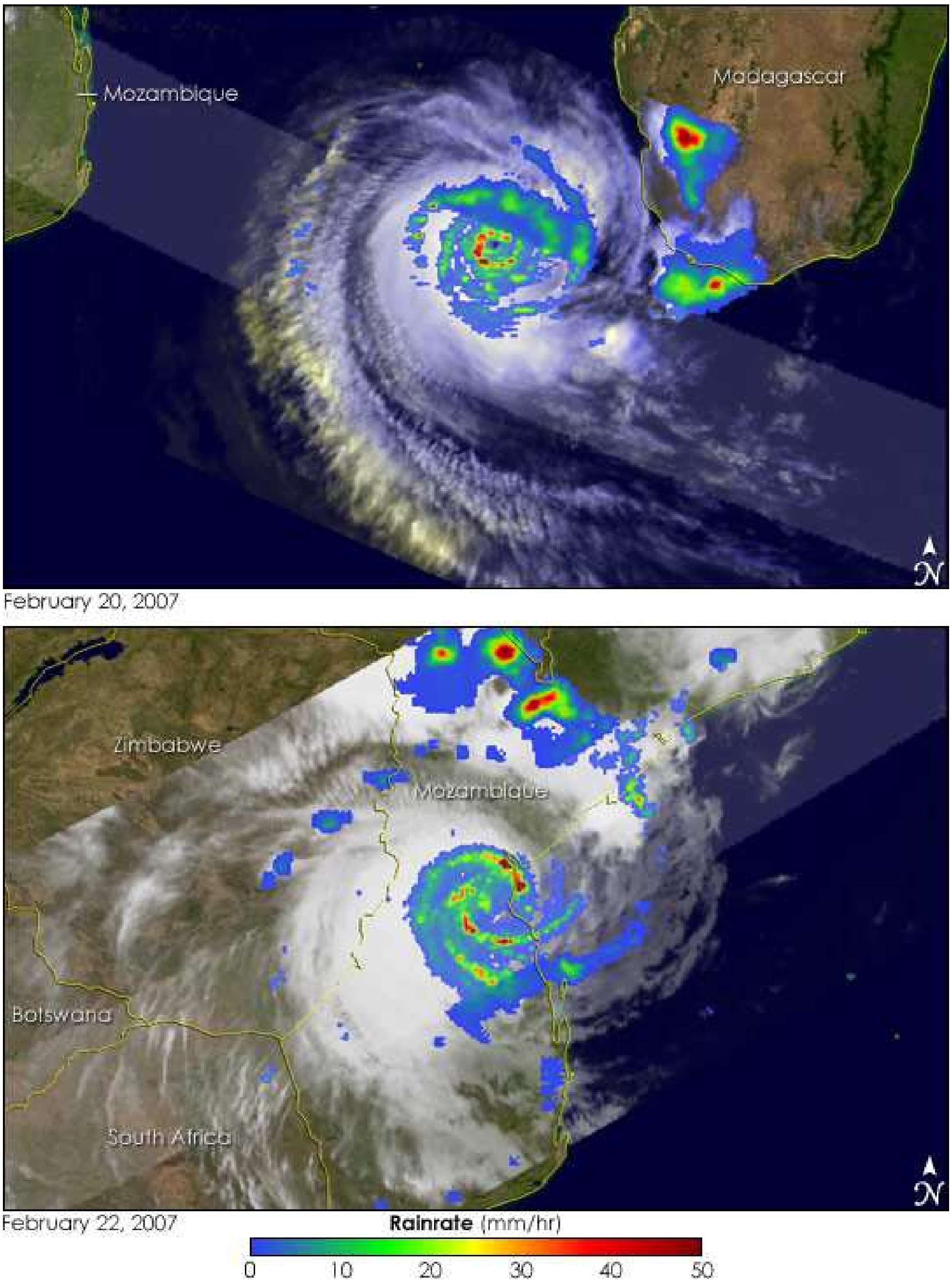


FIG. 3.17: Progression of tropical cyclone Favio around Madagascar and its subsequent landfall on Mozambique on 22 February 2007 (http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=18003, accessed 17 July 2014)

It is therefore likely that tropical cyclone Favio impacted the local climate in the Lowveld tomato producing region for brief periods in January, February, and March 2007. The result was a peculiar combination of high evaporative demand associated with high-pressure cells and overcast conditions associated with low-pressure cells – this had a decidedly negative effect on fruit quality but not total yield (Table 3.5).

3.4.5 Adaptation strategies in the face of climate variation

In the preceding sections, the influence of climate variation on tomato yield and quality was described. Tomato producers may use specific crop management options to avoid, ameliorate, or exploit the negative and positive effects of climate variation on tomato yield and quality.

Early planting results in high yield and a good quality profile (Hanson and May 2006). Therefore, tomato producers should attempt to plant as early as possible after winter to maximise exposure of the mature plant to optimum temperatures. In temperate regions, exposure of the seedling to suboptimal temperatures or frost leads to poor root, foliage and fruit development (Skąpski and Pyzik 1990, Gent 1992, Cuartero and Rodriguez 1994, Venema et al. 2008, Ntatsi et al. 2014). One solution involves the use of cold-tolerant cultivars. Another solution involves the use of specific microbial endophytes that confer cold-tolerance to tomato seedlings (Chen et al. 2014).

Tomato producers may be tempted to use more fertilizers in an attempt to improve plants' declining vigour due to cold or heat stress. However, South African maize producers experienced >50% yield reduction for late plantings, 'regardless of amount of fertilizer applied,' and profitability worsened as more fertilizer was used in an attempt to restore the situation (Rurinda et al. 2013). The same principle applies to tomatoes. Despite increased fertilizer usage, Abd-Alla et al. (1996) reported a 67% reduced plant growth rate and consistent yield deficits of 13-38% for summer plantings. In open field situations, this deficit is much larger due to full exposure to climate and associated risks (rain, wind, hail, insects, soilborne diseases). Producers have to be aware that favourable value-to-cost ratios are achievable at lower fertilizer and irrigation rates despite slight decreases in yield (Sun et al. 2013). Taulavuoria et al. (2014) recently found the effects of nitrogen on frost hardiness to vary between crop type, seasons, nitrogen source and timing of application.

Abdul-Baki et al. (1996) extended the growth season of tomatoes with the use of cover crops because of delayed ripening. This particular management option would not be preferred in a colder climate because of the shorter growing season, where the use of quick maturing cultivars would be a better option (Alvino et al. 1990, Skąpski and Pyzik 1990, Drost and Price 1991).

Mycorrhizae are soilborne fungi that form a symbiotic interaction with a suitable host plant; the host plant provides sugars to the fungus, while the fungus secures insoluble phosphorous, nitrogen and micro-elements from the soil and make these available to the plant (Karandashov and Bucher 2005, Rooney et al. 2009, Zhang et al. 2010a). Producers purchase commercial formulations of mycorrhizae in order to facilitate biological crop nutrient management. Mycorrhizae are associated with soil N and microelement transformations, disease suppression and improved crop resilience (Lioussanne et al. 2008, Vos et al. 2012, Whiteside et al. 2012, Baslam et al. 2013). However, the application of fertilizers negatively affects mycorrhizae (Smith and Barker 2002, Denef et al. 2009, Hu et al. 2009, Chagnon and Bradley 2013). Even high levels of phosphorus in compost inhibit subsequent mycorrhizae interactions (Douds et al. 2006, Cavagnaro 2014). Thus, the plant does not require the services of the fungus if inorganic (or available organic) P supply is unlimited. Furthermore, these fungi are sensitive to fungicides aimed at controlling soilborne fungal pathogens (Trappe et al. 1984, Veeraswamy et al. 1993, Smith et al. 2000, Jin et al. 2013). For these reasons, the contribution of mycorrhizae to crop nutrient supply in the commercial agriculture context has been questioned (Ryan and Kirkegaard 2012, Williams and Hedlund 2013).

Bacterial speck of tomatoes is a particularly destructive disease. Yield losses can reach 75% if plants are infected during the early growth stages, but losses are minimal (5%) when mature plants are infected (Yunis et al. 1980). Late plantings are likely to require above-average pesticide applications because climate conditions are conducive for pest- and disease multiplication and spread (Jones et al. 2000). Therefore, the implementation of synthetic or organic preventive countermeasures safeguards the high yield potential offered by the early planting time and reduces the below-average yields expected during the late planting time.

A key feature of the history of tomato production in South Africa is the dramatic increase in yields (+109%) in the early 2000's with the introduction of indeterminate cultivars, which allowed for sustained high-intensity production on 47% less land (FAOSTAT 2015; see Chapter 2). Also, access to agrotechnology (knowledge, synthetic inputs, information technology) further enhanced productivity where tomato cultivation was already successful. Genetic resistance improves the tomato crop's resilience against climate stress factors (Lammerts van Bueren et al. 2011), saline soil conditions (Flores et al. 2010), low temperatures (Venema et al. 2008), high temperatures (El-Abd and El-Beltagy 1996), high altitude conditions (Ahmad et al. 2007), and disease resistance (Pogonyi et al. 2005, Lopez-Perez et al. 2006, Wang et al. 2009). However, the efficacy of genetic traits is subject to climate conditions and crop management. For example, Hong et al. (2012)

reduced bacterial disease on soybeans by delayed planting of susceptible cultivars while resistant cultivars performed best when planted in the optimum planting window. Similar findings were reported for tomatoes (Skąpski and Pyzik 1990). It is not uncommon for a range of cultivars to respond differently when cultivated under the same soil, climate and management conditions. For example, of the eleven tomato cultivars tested for high altitude cultivation in Pakistan, the total yields ranged from 20 to 68 t ha^{-1} (Ahmad et al. 2007). Cultivar selection trials should therefore be a continuous event in order to optimize production within the best planting time, but also to investigate whether unique cultivar traits allowed for sustainable production during riskier planting times (or combinations of interactions between environment and biological factors) (Moreno et al. 2003).

3.5 Conclusions

Insight was gained into how climate variability during specific growth stages influenced the tomato plant's cumulative productivity in the Lowveld bioregion of South Africa. Such an understanding could inform strategies for increasing tomato production in suitable agroecological zones within southern Africa. Tomato yield and quality was acceptable during the early and optimum planting windows. This was not the case for the late planting window (from spring to summer). Climate conditions in the late planting time exposed the tomato to yield-limiting high temperatures, high relative humidities and high atmospheric evaporative demand. Together with these physiological stresses, a range of pests and diseases assailed the plant due to the conducive climate conditions. Excessive or persistent low-intensity rainfall and long periods of overcast conditions added to the distress of seedlings planted in this period. Altogether, total and high quality yields during the late planting time were 17% and 44% less than during the early and optimum planting times. Producers will be hard-pressed to maintain yields, but catastrophic losses are avoidable through the consistent use of effective crop protection technologies and adaptive irrigation scheduling. It remains an open question whether specific soil or crop management variables could be used to avoid or exploit challenging or favourable climate conditions within each planting window. Tomato producers in the SADC region can benefit from the findings of this chapter by appreciating the basic climatic requirements of the tomato crop and noting the importance of planting time optimization. More research is needed to explore the interactions between climate, soil, and crop management variables and the association with tomato yield and quality (Chapter 4).

CHAPTER 4

INTERACTIONS BETWEEN CLIMATE, SOIL, AND CROP MANAGEMENT VARIABLES INFLUENCE TOMATO YIELD AND QUALITY IN THE LOWVELD BIOREGION OF SOUTH AFRICA[2]

Abstract

South African open field tomato production occurs primarily in the Limpopo province and contributes significantly to the socio-economic stability of thousands of employees, suppliers and their dependents. Increasing production costs force these tomato producers to intensify production. Since 2000, these tomato producers practiced intensive open field tomato production using a combination of synthetic and organic crop management technologies. The objective of this study was to analyse the production practices and the resultant yields in terms of the following: soil quality (texture and chemistry), synthetic fertilizer usage, synthetic and organic pest and disease control, soil conditioning via organic matter additions, microbial inoculants, and prevailing climatic conditions. The Environmental Impact Quotient (EIQ) was used to calculate the relative ecological impact of synthetic pesticide usage. We studied these interactions for three different planting times within the year over an eight-year period by means of Classification and Regression Tree (CART) analysis. For the early planting time, a combination of suitable climatic conditions, optimum use of fermented plant extracts, and optimum potassium nutrition management characterized successful tomato production. High-yield tomato production in the optimum planting time hinged on high ecological impact pest and disease control, and cultivation on low clay content soils. No yield-limiting or –enhancing associations with organic technologies were detected for this planting period. Tomato cultivation in the late planting time was problematic due to the negative effect of unfavourable climatic conditions on tomato yield and quality. In conclusion, complex interactions between biotic and abiotic variables influence tomato yield and quality. Yield decrease was observed when specific organic and synthetic crop management technologies were used excessively or at suboptimal levels. Sustainable open field tomato production depends on the integrated use of synthetic and organic crop nutrition and protection technologies, optimum planting times, disease-resistant genetic material, and cultivation in healthy soils.

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[2] This chapter was presented as a poster at the Agriculture and Climate Change Conference, 15-17 February 2015, Amsterdam, The Netherlands

Keywords: Climate, Environmental impact quotient, Fermented plant extracts, Fertilizer, Interactions, Soil

4.1 Introduction

South Africa is the leading vegetable producer in Southern Africa and tomato production ranks fourth in the South African vegetable production sector (FAOSTAT 2015). South African open field tomato production occurs primarily in the Limpopo province and contributes significantly to the socio-economic stability of thousands of employees, suppliers and their dependents. The economic sustainability of tomato production in South Africa hinges on fruit quality, continuity of supply during the year, and prevailing market prices. Increasing production costs forced these tomato producers to intensify production – high yields are no longer a luxury, but an economic necessity.

Although the basic theoretical prerequisites of sustainable agriculture are described in literature, there is a shortage of case studies where these precepts have been tested under real-world commercial agriculture conditions. During the early 2000's, tomato producers in the Limpopo bioregion of South Africa implemented a 'nature-friendly' production system in order to ameliorate the negative effects of long-term conventional farming practices. This approach to commercial tomato production aimed to harness the principles of natural ecosystems for sustainable crop production, without forfeiting the benefits of technology and science. These tomato producers aimed to avoid the pitfalls of unsustainable industrial agriculture and unproductive organic systems, while retaining those aspects that were useful in the commercial agriculture context. According to Prinsloo et al. (2005), the main philosophical tenets of the production system are the following:

- To balance the mineral elements in the soil
- To increase soil organic matter content
- To improve soil microbial life and diversity
- To optimize pest and disease management
- To optimize strategic and tactical water management

This approach to farming is not novel and aspects thereof are synonymous with a range of related farming philosophies such as Conservation Agriculture (reduced tillage, integrated pest management, integration with livestock), Kyusei Nature Farming (use of Effective Microorganisms® and fermented plant extracts), biological farming (application of microbial ‘foods’ to soils), and aspects of organic farming as practiced in the West (compost and compost tea). This particular example of eco-agriculture, or ‘nature-friendly farming’, as practiced by these tomato producers in South Africa, was previously described in the scientific literature, albeit superficially (Uphoff and Thies 2011). This thesis is the first scientific report on this particular production system.

For an eight-year period (2003-2010), these South African tomato farmers practiced intensive open field tomato production using a combination of synthetic and organic crop management technologies. In order to increase our understanding of the factors that influence crop yields, especially in the face of global climate variation, analysis of increasingly complex datasets is required (Lobell et al. 2007, Ortiz et al. 2007, Doré et al. 2011). Internationally, tomato production is characterized by above-average water, nutrient and pest/disease control requirements. Therefore, it is in the interest of the sustainable agriculture debate in general and the global tomato production industry in particular, to take note of the achievements and failures of these South African tomato farmers.

The objective of this study was to analyse the production practices and the resultant yields in terms of the following: soil quality (texture and chemistry), synthetic fertilizer usage, synthetic and organic pest and disease control, ecological impact, soil conditioning via organic matter application, microbial inoculants, and prevailing climate conditions. We hypothesized that the nature-friendly crop management system increased the resilience of the tomato crop in the face of climate variation. If this hypothesis is not rejected, the identification of specific soil and crop management interventions may aid tomato producers to sustain yields in the face of seasonal and annual climate variation.

4.2 Materials and methods

4.2.1 Tomato production region

A detailed description of the production region appears in Chapter 3 (section 3.2.1). The main climate characteristics of the study area are summarized in Fig. 3.2 and Fig. 3.3 in Chapter 3.

4.2.2 Tomato production system

A detailed description of the production system appears in Chapter 3 (section 3.2.2).

4.2.3 Data sets

To analyse the production practices and the resultant yields, 1 024 tomato cultivation events in the Lowveld production area were assessed for the period 2003 to 2010. Detailed soil and crop management information was obtained from the producers in the form of accounting records associated with each field. This dataset contained more than 300 000 weekly transactions for 358 crop and soil management commodities. It took nearly two years to clean, order and compile the final dataset before data analysis commenced. The final dataset contained 95 variables (Table 4.1).

TABLE 4.1: Descriptive statistics of climate, soil and crop management variables related to 1 024 tomato cultivation events in the Lowveld region of South Africa. All values are cumulative values (unless indicated otherwise) for the 25-week duration of each tomato production event.

Variables[a]	Units	Minimum	25th percentile	Mean	75th percentile	Maximum
Yield and quality						
Total yield	t ha^{-1}	30.0	60.7	79.6	96.1	145.5
Marketable yield	t ha^{-1}	1.6	22.3	34.4	44.8	110.5
Field history						
Fallow period	weeks	38.0	242.3	470.4	462.9	1 594.0
Times cultivated prior	count	1.0	2.0	2.4	3.0	9.0
Soil management						
Cattle and chicken manure mix (1:1)	t ha^{-1}	0.0	0.0	0.4	0.0	7.8
Compost	t ha^{-1}	0.0	0.0	12.3	16.7	113.6
Guano (bird and bat)	t ha^{-1}	0.0	0.0	0.2	0.2	3.8
Gypsum	t ha^{-1}	0.0	0.0	1.1	1.5	5.8
Lime	t ha^{-1}	0.0	0.0	1.1	4.6	25.6
Crop management (synthetic weed, pest and disease control)						
Adjuvants	kg ai ha^{-1}	0.0	1.6	19.2	23.6	234.0
Biocides	kg ai ha^{-1}	2.7	16.7	30.2	29.1	130.9
Herbicides	kg ai ha^{-1}	0.0	1.9	3.4	4.1	17.5
Insecticides	kg ai ha^{-1}	2.2	11.4	17.1	21.6	175.3
Non-toxic silica	kg ai ha^{-1}	0.0	0.0	1.3	0.0	21.3
Crop management (synthetic crop nutrition)						
K	kg K ha^{-1}	101.1	277.7	406.0	473.0	2 321.1
N	kg N ha^{-1}	44.2	130.7	199.2	232.9	878.4
P	kg P ha^{-1}	1.6	57.0	87.0	102.0	453.7
K:N	ratio	0.8	1.8	2.1	2.4	3.7
K:P	ratio	1.3	3.4	5.5	6.6	82.2
N:P	ratio	0.8	1.5	2.7	3.3	30.3
Crop management (biological)						
BCA (bacteria)	kg ai ha^{-1}	0.2	97.4	259.1	347.6	1 142.2
BCA (fungi)	kg ai ha^{-1}	0.0	0.0	0.0	0.0	0.2
BCA (yeast)	kg ai ha^{-1}	0.0	0.0	0.0	0.0	0.3
Compost tea	l ha^{-1}	0.0	433.6	1 259.9	1 661.9	5 817.1
Effective Microorganisms®	l ha^{-1}	0.0	27.7	90.8	122.0	545.8

TABLE 4.1 (Continued)

Variables	Units	Minimum	25th percentile	Mean	75th percentile	Maximum
Crop management (organic nutrition, pest and disease control)						
Corn starch	l ha^{-1}	0.0	0.0	7.1	9.2	60.1
Ecklonia maxima extract	l ha^{-1}	0.0	0.0	1.4	1.9	14.1
FPE-Aloe	l ha^{-1}	0.0	0.0	7.5	1.9	100.5
FPE-Garlic/Neem	l ha^{-1}	0.0	0.0	5.8	0.0	73.5
FPE-Lantana	l ha^{-1}	0.0	11.0	52.7	76.9	457.9
FPE-Lemon	l ha^{-1}	0.0	0.0	6.9	0.0	96.1
FPE-Silica	l ha^{-1}	0.0	0.0	8.3	7.9	82.0
Fulvic acid	kg ai ha^{-1}	0.0	1.2	7.5	11.0	46.9
Humic acid	kg ai ha^{-1}	0.0	1.9	7.6	10.8	81.8
Molasses	l ha^{-1}	0.0	0.0	4.6	6.3	55.2
Environmental Impact Quotient (EIQ)						
EIQ (total)	score	335.8	1 317.0	2 157.0	2 425.6	9 571.7
Consumer	score	84.1	338.4	565.4	636.7	2 535.7
Ecosystem:	score	648.7	2 518.2	4 159.7	4 486.0	18 936.6
• Bee	score	98.9	470.9	722.3	789.3	3 863.4
• Beneficials	score	224.2	948.9	1 513.4	1 732.3	6 964.2
• Birds	score	159.2	654.2	1 111.8	1 292.2	6 134.9
• Fish	score	127.4	453.9	811.2	990.5	4 194.6
• Terrestrial	score	482.7	2 109.5	3 347.6	3 796.1	14 739.0
Worker	score	274.7	1 017.2	1 749.5	2 049.9	7 242.4
Soil quality (texture)						
Sand (0-15 cm)	%	38.0	77.0	80.5	85.2	95.0
Silt (0-15 cm)	%	1.0	5.0	6.8	8.5	22.0
Clay (0-15 cm)	%	2.0	8.5	12.3	15.3	42.0
Sand (15-30 cm)	%	47.0	75.5	79.8	84.5	93.0
Silt (15-30 cm)	%	1.0	5.0	6.9	8.5	53.3
Clay (15-30 cm)	%	3.0	9.0	13.1	16.0	43.0
Sand (30-45 cm)	%	49.0	74.0	78.2	84.0	93.0
Silt (30-45 cm)	%	1.0	5.0	6.9	8.3	53.3
Clay (30-45 cm)	%	2.3	10.0	14.6	18.0	46.0
Soil quality (chemistry)						
CEC	cmol(+) kg^{-1}	1.7	5.0	7.2	8.7	29.7
Ca	mg kg^{-1}	149.0	608.3	925.7	1 111.9	5 487.0
	% bs	31.7	58.9	63.1	67.0	94.5
K	mg kg^{-1}	6.0	129.1	204.2	260.0	1 637.5
	% bs	0.5	5.5	7.8	9.7	33.9
Mg	mg kg^{-1}	7.0	164.0	237.0	292.8	1 136.3
	% bs	0.6	24.2	28.0	31.6	57.7
Na	mg kg^{-1}	4.0	9.6	16.7	18.0	556.0
	% bs	0.1	0.6	1.1	1.4	16.1

TABLE 4.1 (Continued)

Variables	**Units**	**Minimum**	**25th percentile**	**Mean**	**75th percentile**	**Maximum**
Soil quality (chemistry) (continued)						
P (Bray I)	mg kg^{-1}	1.0	24.0	45.6	61.7	230.0
pH (KCl)	pH	4.0	5.2	5.5	5.8	7.1
Ca:Mg	ratio	0.9	3.1	4.7	4.6	286.5
(Ca+Mg)/K	ratio	0.9	4.3	7.6	8.4	77.7
Mg:K	ratio	0.0	0.9	1.7	1.8	24.3
Weather						
Atm. pressure (min)	mbar	917.3	997.8	992.6	1 012.8	1 050.4
Atm. pressure (avg)	mbar	919.8	1 000.7	995.5	1 016.0	1 054.3
Atm. pressure (max)	mbar	922.0	1 003.3	998.4	1 019.0	1 058.4
Cold Units	°C	0.0	126.0	357.0	530.5	1 202.6
Delta T	°C	7.1	11.1	12.0	13.2	15.8
Dew point (low)	°C	-8.1	5.2	8.2	11.4	16.3
Dew point (avg)	°C	1.2	8.5	11.2	14.1	17.9
Dew point (max)	°C	5.7	11.6	13.9	16.4	19.5
Evaporative demand	mm d^{-1}	1.1	1.8	2.3	2.8	4.7
ET (25-week)	mm	185.0	312.6	403.3	494.5	819.5
Heat Units	°C	445.2	1240.5	1 556.4	1 873.0	2 222.5
Rain	mm	0.0	55.0	219.4	325.3	985.1
Rel. humidity (min)	%	20.7	33.7	39.1	44.1	57.5
Rel. humidity (avg)	%	45.9	54.4	60.0	65.1	77.4
Rel. humidity (max)	%	62.5	77.0	80.5	84.4	97.3
Solar radiation (avg)	watt m^{-2}	158.4	183.4	202.4	211.1	355.7
Solar radiation (avg max)	watt m^{-2}	211.3	243.3	277.8	303.7	473.4
Solar radiation(max)	watt m^{-2}	759.0	831.3	931.5	1 032.2	1 164.6
Temperature (min)	°C	7.4	12.6	14.9	17.2	20.9
Temperature (avg)	°C	14.3	18.9	20.7	22.5	24.6
Temperature (max)	°C	21.6	25.6	26.9	28.1	30.3
Wind chill (min)	°C	7.6	12.7	15.0	17.3	21.2
Wind chill (avg)	°C	14.1	18.8	20.6	22.4	24.5
Wind chill (max)	°C	21.1	25.2	26.5	27.8	29.9
Wind speed (avg)	km h^{-1}	2.6	3.9	4.7	5.6	7.3
Wind speed (max)	km h^{-1}	22.5	27.6	29.8	32.0	36.6

[a] %bs = % base saturation; Atm. Pressure = atmospheric pressure; BCA = biological control agent; CEC = cation exchange capacity; Delta T = difference between maximum and minimum temperatures; ET (25-week) = cumulative evaporative demand over 25-week production period; FPE = fermented plant extract; Rel. humidity = relative humidity

4.2.3.1 Field history

The duration of the preceding fallow period was calculated for every tomato production event. In addition, the number of times a particular field was cultivated since 1994 was also calculated from the producers' field history records.

4.2.3.2 Soil management

Compost, gypsum and/or lime were applied to the tilled soils prior to seedling planting. The tomato producers also experimented briefly with guano (bat and bird) and a 1:1 mixture of cattle and chicken manure. The gypsum and lime were broadcasted onto the tilled soils, but the compost and manures were incorporated into the ridge. The actual quantities applied depended on the soil chemistry test results taken three months earlier.

4.2.3.3 Synthetic crop management: fertilizers, herbicides and pesticides

A range of synthetic sources of N, P and K were used over the study period. The use of a particular commodity or formulation depended on price, availability, soil quality and prevailing crop health. Herbicides were used before planting and upon termination of the crop after the final harvest; the major active ingredient used was paraquat-dichloride (Gramoxone, Syngenta SA). A wide range of synthetic fungicides, bactericides and insecticides were used during the study period. Data for the herbicides and pesticides were reported on active ingredient (a.i.) basis. This information was used to calculate the ecological impact of crop production events using the 2012 version of the Environmental Impact Quotient (EIQ) model (Kovach et al. 1992).

4.2.3.4 Environmental impact

The EIQ is a composite indicator for calculating the relative impact of agricultural pesticides, at field utilization rates, on the consumer, worker and the ecosystem. The ecosystem impact score is a composite of the relative impacts on fish, birds, bees, beneficial organisms, and the terrestrial environment in general (e.g., leaching potential and persistence).

4.2.3.5 Organic crop management

A range of commercial bacterial, fungal and yeast biological control agents (BCAs) were used during the study period. The selection and application of these interventions were based on the product's availability, field conditions and the identified pest or disease. To facilitate data analysis, the use of these commodities was expressed on a biological a.i. basis as 0.66 g kg^{-1} and 1.66 g kg^{-1} for bacterial and fungal products respectively. This was done using the stated a.i. concentration (e.g., bacterial colony forming units, fungal spore counts, etc.) to calculate the relative inoculum biomass, the biovolume of bacteria and fungal spores (2 μm^3) and yeasts (5 μm^3) and the cellular density conversion factor of 0.333 g cm^{-3} (Van Veen and Paul 1979).

In addition, the producers also consistently used compost tea and Effective Microorganisms®. Given the complexity of the microbial populations of these on-farm preparations, the application of these liquid organic technologies was reported as l ha^{-1}.

The tomato producers used Effective Microorganisms® to produce fermented plant extracts (FPE) from indigenous *Aloe* spp. (FPE-Aloe), a mixture of *Tulbaghia violaceae* (indigenous wild garlic) and commercial neem oil (*Azadirachta indica*) (FPE-garlic/neem), *Lantana camara* (FPE-Lantana), lemon (FPE-lemon) and commercial non-toxic silica (FPE-Silica). These FPEs were produced by the producers themselves in crude 1 000 l plastic containers in a temperature-controlled room. Application rates were reported on a l ha^{-1} basis because of the microbial and biochemical complexity of these mixtures.

Commercially available humic and fulvic acid formulations, corn starch, molasses and commercial extracts of the indigenous seaweed *Ecklonia maxima* were used by the producers to address soil quality and crop health concerns.

4.2.3.6 Soil analyses

Soil samples were taken with an auger three months before field preparation activities commenced and analysed according to standard methods (The Non-affiliated Soil Analyses Work Committee 1990) by a commercial soil-testing laboratory (Agrilab, Tzaneen). Sand, silt, and clay content were determined with the hydrometer method on samples taken at 0-15 cm, 15-30 cm and 30-45 cm depths. Soil pH was analysed in 1.0 M KCl. Soil P (Bray I) was extracted at pH = 2.6 with 0.025M HCl and 0.03M NH_4F. Total extractable cations, namely K, Ca, Mg and Na, were extracted at pH = 7 with 0.2 M ammonium acetate. Soil K, Ca, Mg and Na content results were reported as exchangeable (mg kg^{-1}) and base saturation basis (%bs).

4.2.3.7 Weather data

A detailed description of the climate dataset and related calculations appear in Chapter 3 (section 3.2.3).

Producers indicated that the economic breakeven yield was 80 t ha^{-1} in 2012 and this was used to delineate the planting time as 'early' (362 cultivation events), 'optimum' (473 cultivation events) or 'late' (189 cultivation events) (see Fig. 3.1, Chapter 3, section 3.3.1).

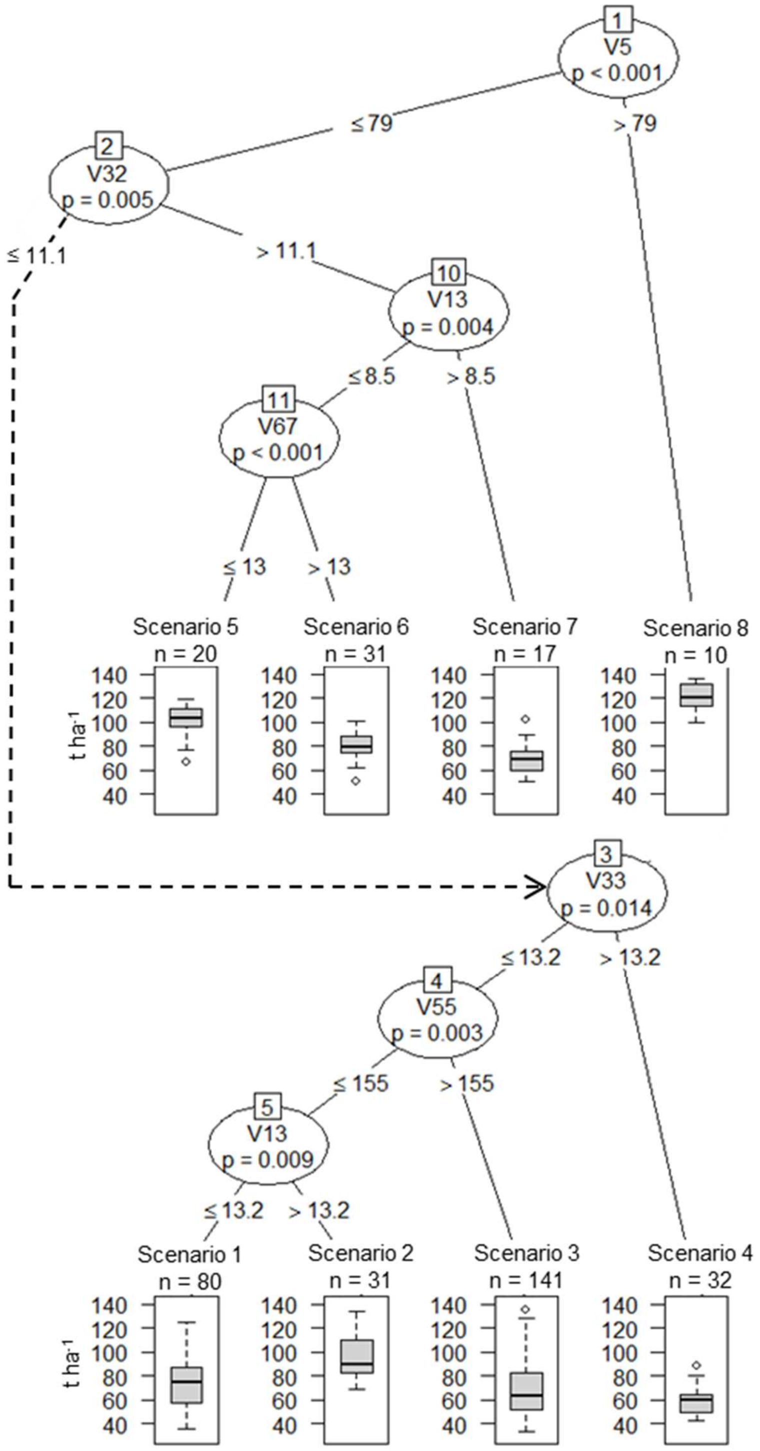
4.2.4 Data analysis

Univariate statistics and correlation matrix PCA were performed with PAST 2.17b (Hammer et al. 2001). Classification and regression tree (CART) analysis was performed with R using *ctree* package (www.r-project.com). To improve the resolution of the analyses, and reduce the dominating effect of climate variables associated with normal seasonal changes, CART analysis was applied separately to each planting time subset of the master dataset. Statistical significance was established at $\alpha = 0.05$. Error bars in graphs indicate the standard error of the means (SEM).

4.3 Results

4.3.1 Early planting time

Complex interactions between soil, crop management and climate variables influenced tomato yield in the early planting time (Fig. 4.1).



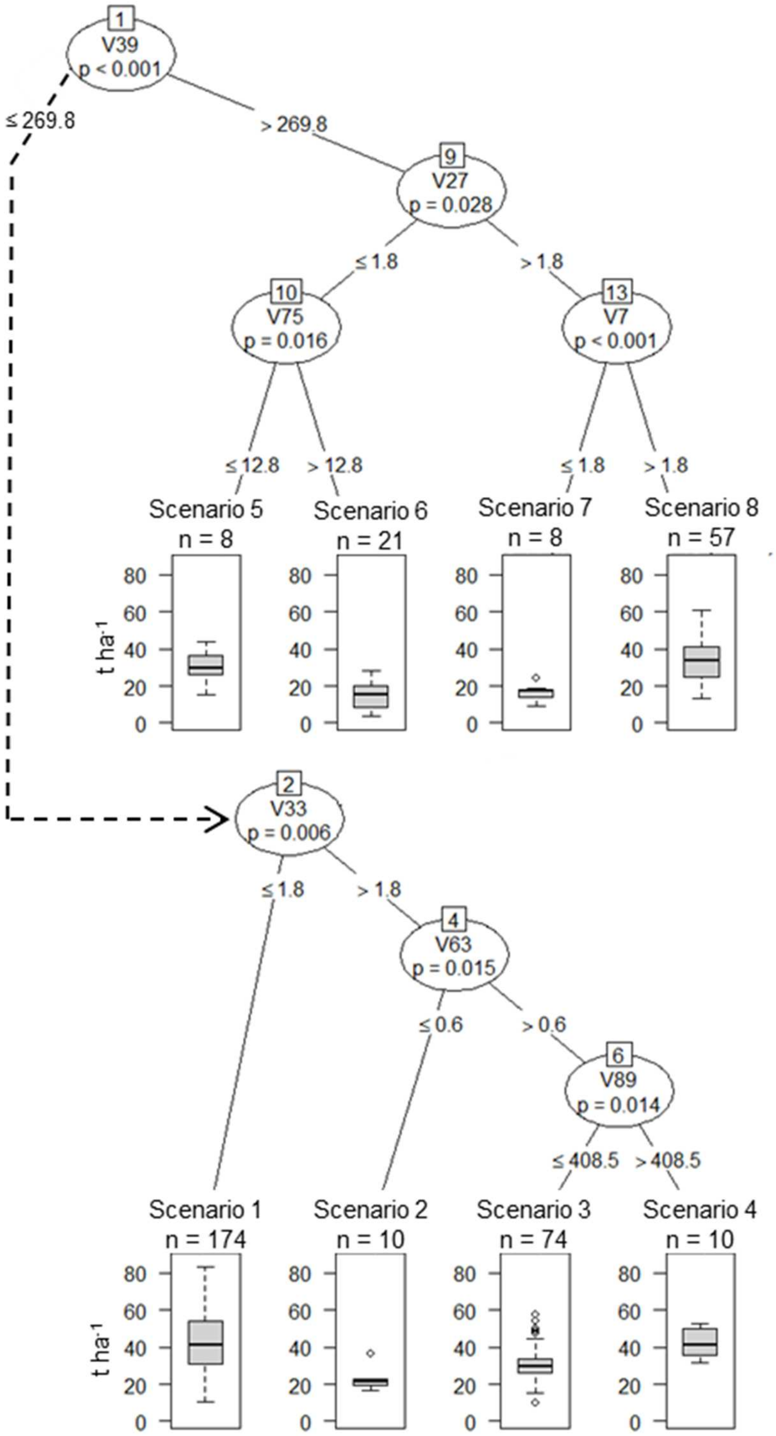
Vertical axes represent total yield. Key: V5 (adjuvant, kg ai ha^{-1}), V13 (humic acid, kg ai ha^{-1}), V32 (FPE-Aloe, l ha^{-1}), V33 (EM-silica, l ha^{-1}), V55 (soil potassium, mg kg^{-1}), V67 (minimum temperature, ^{o}C). All nodes and levels are shown.

FIG. 4.1: The influence of interactions between soil quality, crop management, and climate variables on total tomato yield during the early planting time

High usage of adjuvants (primarily oils and soaps) characterized the highest yield scenario (scenario 8). The lowest yield scenario (scenario 4), was characterized by reduced usage of adjuvants (≤79 l ha^{-1}), and ≤11.1 l ha^{-1} of *Aloe* spp. fermented plant extract (FPE-Aloe) but >13.2 l ha^{-1} of EM-Silica. However, scenarios 3 and 1 occurred most frequently and the difference between low and high yield hinged on the soil potassium content: the productivity of low-potassium soils (≤155 mg kg^{-1}) increased 27% when >13.2 l ha^{-1} of commercial humic acids was applied (scenario 2).

The key climatic feature of the early planting time was the decrease of rain towards the onset of the milder winter period. Although very erratic, cumulative rainfall per 25-week season can be very high during this time of the year (minimum: 0 mm; mean: 131 mm; maximum: 516 mm; coefficient of variation: 95%). However, this was not a significant yield-limiting factor in this dataset. The onset of cold temperatures usually signalled the end of the tomato growing season in areas with frost, but in this production region, the onset of colder temperatures was associated with higher yields (scenarios 5 vs 6). When the average minimum temperature during the 25-week cultivation season was above 13^{o}C, the yield was lower (80.0 t ha^{-1}) than when it was below 13^{o}C (101.0 t ha^{-1}). This result was difficult to explain given the base temperature for tomatoes is 10-12^{o}C. This result may imply that yield-limiting factors, such as the onset of disease, was limited at the lower temperature and less so at the higher minimum temperature. It may also indicate the minimum temperatures did not reach damaging levels and that other variables not measured in this study were not limiting.

Complex interactions between soil, crop management and climate variables influenced high quality tomato yield in the early planting time (Fig. 4.2).



Vertical axes represent high quality yield. Key: V7 (herbicides, kg ai ha^{-1}), V27 (synthetic K:N fertilizers, ratio), V33 (EM-Silica, l ha^{-1}), V39 (guano, kg ha^{-1}), V63 (exchangeable soil Na, %), V75 (maximum dew point, ^{o}C), V89 (cumulative evaporative demand, mm).

FIG. 4.2: The influence of interactions between soil quality, crop management, and climate variables on high quality tomato yield during the early planting time

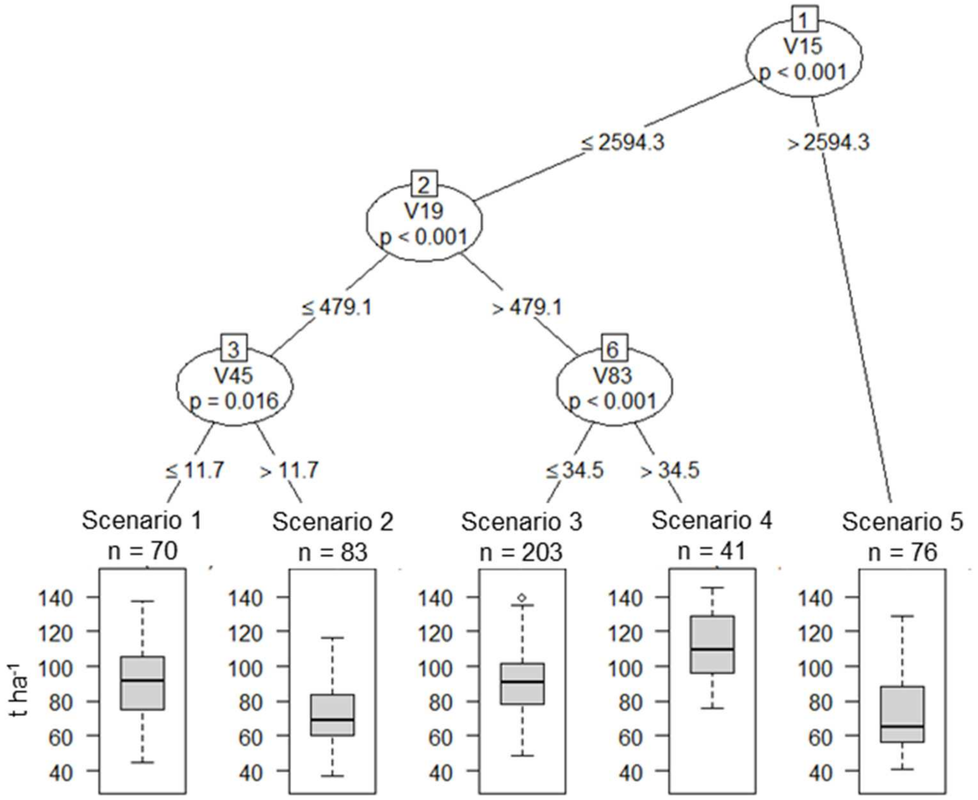
The use of high levels bird and bat guano as a micronutrient supplement was associated with low quality yield (23.2 t ha^{-1}) when applied at >269.8 kg ha^{-1} (Scenarios 5-8). High quality yield was significantly higher (34.4 t ha^{-1}; $P < 0.001$) at reduced applications of guano (≤269.8 kg ha^{-1}). At the ≤269.8 kg ha^{-1} guano application rate, which represented the dominant situation in the dataset (n = 268, 74%), interactions between the use of EM-Silica, the exchangeable soil Na content, and the cumulative evaporative demand were associated with differential high quality yield outcomes. EM-Silica appeared to be effective at very low application rates (≤1.8 l ha^{-1}; scenario 1), or when the cumulative evaporative demand exceeded 408.5 mm (scenario 4).

From this CART analysis it was not possible to find realistic differences between scenarios 1 and 4, given that the average high quality yields were very similar. Additional variables probably explained the substantial variation in that subset (scenario 1, CV = 37%), however a dedicated CART analysis performed on the dataset for scenario 1 did not yield any additional splits or branches.

In the high guano application scenarios (5-8), high quality yield hinged on three variables: K:N ratio of synthetic fertilizers, dew point and herbicide usage. When the K:N ratio was low (≤1.8) and the prevailing climate was cooler (≤12.8°C maximum dew point), the high quality yield was nearly double (30.5 t ha^{-1} vs 15.3 t ha^{-1}, $P = 0.016$) than when the climate was warmer (>12.8°C maximum dew point). On the other hand, when the K:N ratio was ideal for optimum tomato production (>1.8), high quality yield was significantly higher ($P < 0.001$) when proper synthetic weed control was exercised (scenario 8).

4.3.2 Optimum planting time

Interactions between soil, crop management and climate variables influenced tomato yield in the early planting time (Fig. 4.3).



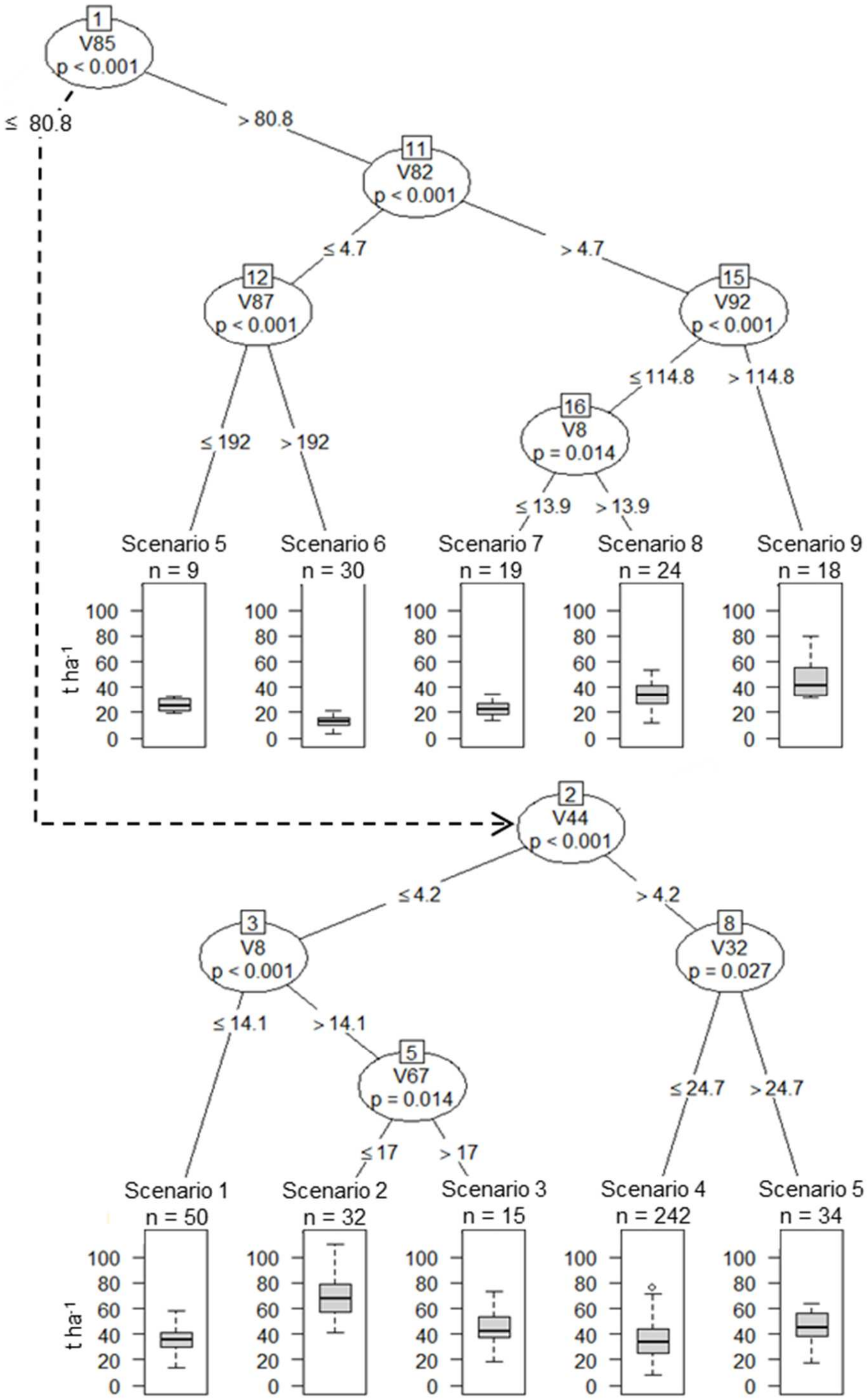
Vertical axes represent total yield. Key: V15 (worker impact quotient, score), V19 (bee impact quotient, score), V45 (soil clay content at 0-15 cm, %), V83 (average maximum wind speed during 25-week production season, km h^{-1}). All nodes and levels are shown.

FIG. 4.3: The influence of interactions between soil quality, crop management, and climate variables on total tomato yield during the optimum planting time

Usage of biocides and insecticides that increase the cumulative worker impact quotient score characterized the lowest yield scenario (scenario 5). The usage of biocides and pesticides that increase the ecological impact on bees were associated with the high yield scenarios (scenario 3 and 4); the difference between the yield of scenarios 3 and 4 hinged on the average maximum wind speed being above 34.5 km h^{-1}.

For the scenarios characterized by low ecological impact pest and disease control programs (scenarios 1 and 2), the difference between high and low yield hinged on the soil clay content at 0-15 cm depth. Tomato yield was higher (90.2 t ha^{-1}) when produced on soils with ≤11.7% clay and significantly lower (73.2 t ha^{-1}, $P = 0.016$) at >11.7% soil clay content.

Relative humidity influenced severely the high quality tomato yield in the optimum planting time (Fig. 4.4).



Vertical axes represent high quality yield. Key: V8 (synthetic insecticides, kg ai ha^{-1}), V32 (FPE-Aloe, l ha^{-1}), V44 (soil silt content at 0-15 cm, %), V67 (minimum temperature, °C), V82 (average wind speed, km h^{-1}), V85 (maximum relative humidity, %), V87 (cumulative rainfall, mm), V92 (cumulative cold units, GDD). All nodes and levels are shown.

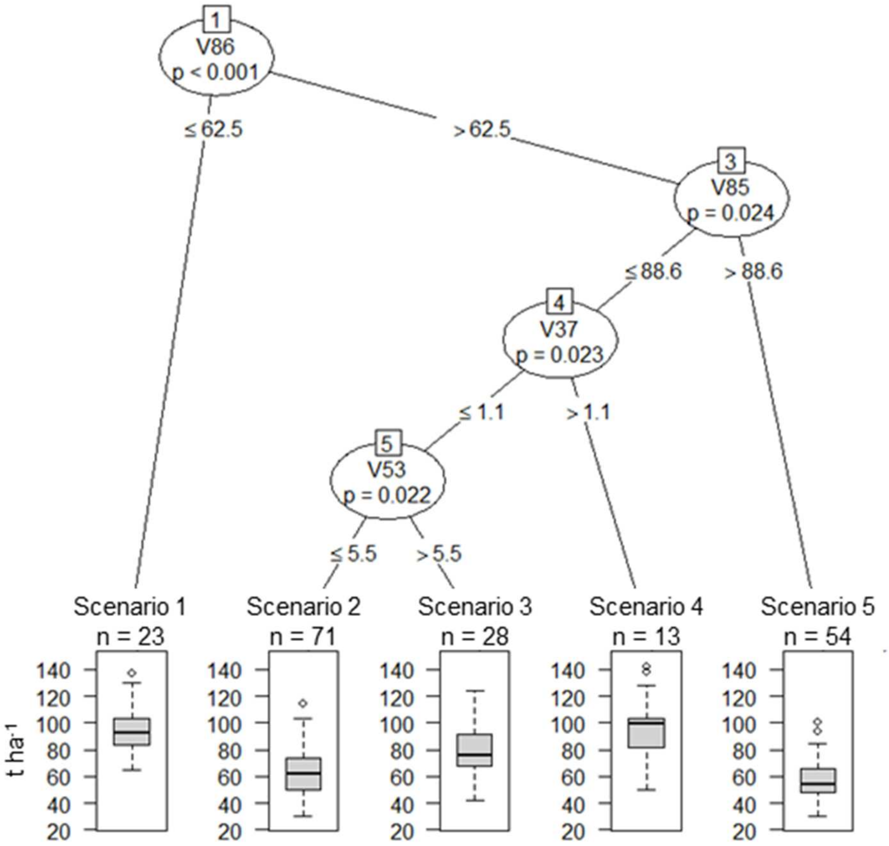
FIG. 4.4: The influence of interactions between soil quality, crop management, and climate variables on high quality tomato yield during the optimum planting time

When the average relative humidity was ≤80.8%, the average high quality yield was higher than when the average relative humidity exceeded 80.8% (44.3 t ha^{-1} vs 28.2 t ha^{-1}, $P < 0.001$). Also, at the ≤80.8% relative humidity level, effective management options were identifiable in the form of, 1) the use of low-silt soils (≤4.2%), and 2) high usage of synthetic insecticides (>14.1 kg ai ha^{-1}).

However, when the average relative humidity exceeded the 80.8% level, high quality yields were associated only with high average wind speeds (>4.7 km h^{-1}) and cumulative cold units >114.8^{o}C (scenario 8). High quality yields were dismal when the average wind speed was low (<4.7 km h^{-1}) and any rainfall occurred (scenarios 5 and 6).

4.3.3 Late planting time

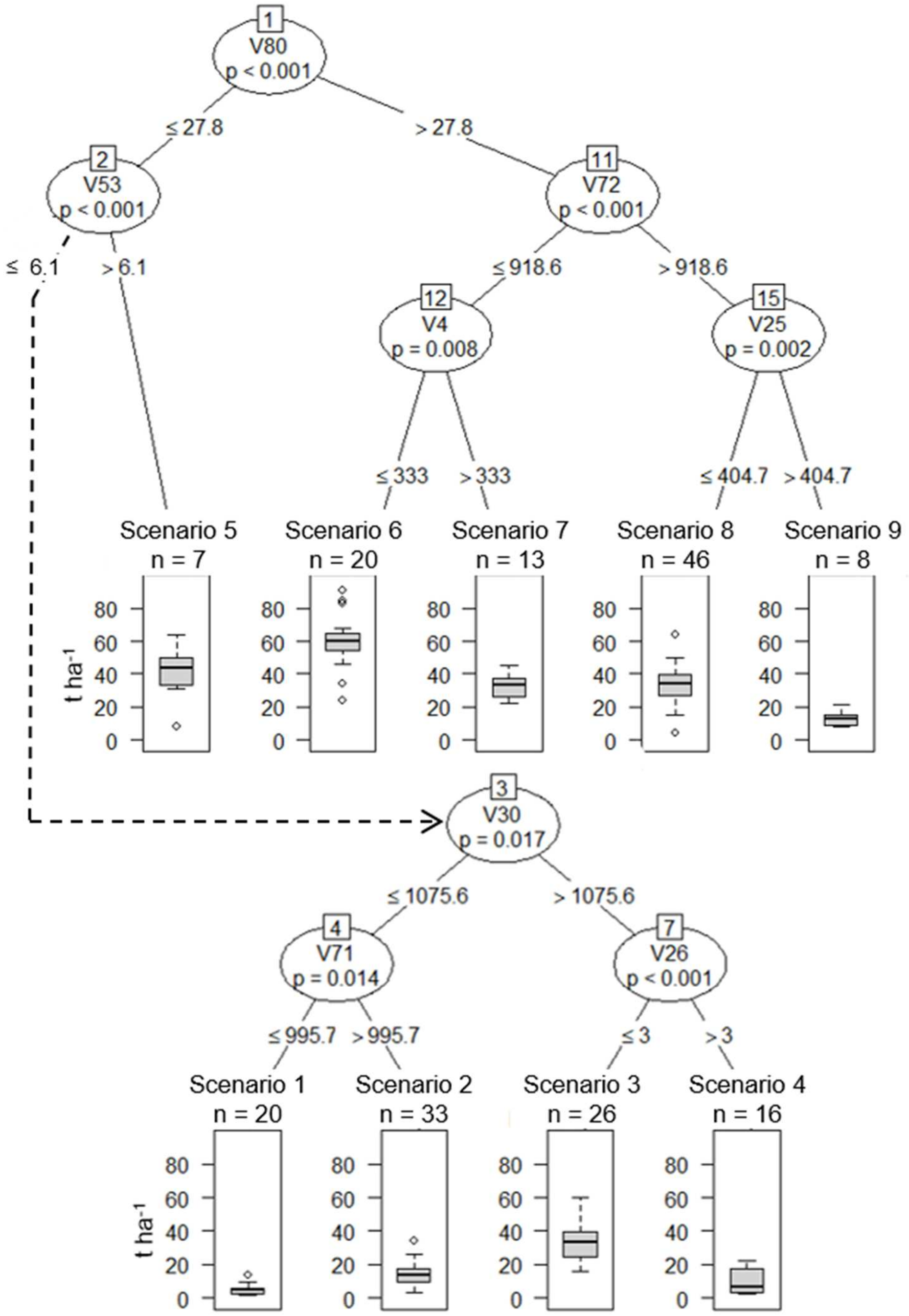
Interactions between soil, crop management and climate variables influenced tomato yield in the late planting time (Fig. 4.5). Very high yields were recorded when the average relative humidity was ≤62.5% (scenario 1). Very low yields were recorded when the average maximum relative humidity exceeded 88.6% (scenario 5). The highest yield scenario was characterized by favourable climate conditions (average maximum relative humidity ≤88.6%) and the use of a commercial synthetic silica-based remedy (scenario 4). Soil quality played a role in two scenarios and the difference between an average yield of 62.3 t ha^{-1} and a high total yield of 79.2 t ha^{-1} hinged on the soil pH: yield was significantly lower ($P = 0.022$) when tomatoes were cultivated in acidic soils (pH KCl ≤5.5). In comparison to the early planting time, fewer variables were involved in less complex yield-affecting interactions during the late planting time.



Vertical axes represent total yield. Key: V37 (commercial synthetic silica, l ha^{-1}), V53 (soil pH), V85 (average maximum relative humidity during a 25-week production period, %), V86 (average relative humidity during a 25-week production period, %). All levels are shown.

FIG. 4.5: Influence of interactions between soil quality, crop management, and climate variables on total yield during the late planting time

A combination of climate, crop and soil management variables affected high quality yield in the late planting time (Fig. 4.6).



Vertical axes represent high quality yield. Key: V4 (fallow duration, weeks), V25 (synthetic K fertilizer, kg K ha^{-1}), V26 (synthetic N:P ratio), V30 (gypsum, kg ha^{-1}), V53 (soil pH), V71 (maximum atmospheric pressure, mbar), V72 (minimum atmospheric pressure, mbar), V80 (maximum wind speed, km h^{-1}). All levels are shown.

FIG. 4.6: The influence of interactions between soil quality, crop management, and climate variables on high quality tomato yield during the late planting time

The best high quality yield scenario (6) was associated with maximum average wind speeds >27.8 km h^{-1}, minimum atmospheric pressure ≤918.6 mbar, and rotation periods ≤333 weeks (6.4 years). The lowest high quality yield scenario (1), was associated with lower maximum wind speeds (≤27.8 km h^{-1}), soil pH (KCl) ≤6.1, low gypsum usage (≤1 075.6 kg ha^{-1}), and low atmospheric pressure (≤995.7 mbar). The ability to maintain break-even total yields (~ 80 t ha^{-1}) and achieve increased high quality yields with significantly shorter rotations ($p < 0.001$) during the late planting time demands closer scrutiny of the raw data. Although this result considered only 33 cultivation events, it may provide insight into what ZZ2-Natuurboerdery® actually implies on a practical level without the confounding effect of climate variation encountered in previous CART analysis results. Univariate statistical comparisons indicated that scenarios 6 (short fallow period) and 7 (long fallow period) differed in terms of the synthetic phosphorous fertilizer application rates, the ecosystem impact of the pest- and disease management program, and the soil physical and chemical attributes (Table 4.2).

TABLE 4.2: Comparison of fields planted in the late planting time with short (<333 weeks) and long (>333 weeks) fallow periods based on field and crop management, and soil texture and chemistry.

Variable[a]	**Units**	**Short fallow (n = 20) Mean (SE)**	**Long fallow (n = 13) Mean (SE)**	**T-test P-value**[b]
High quality yield	t ha^{-1}	60.1 (3.5)	31.4 (1.9)	<0.001
Field and crop management				
Fallow duration	weeks	275.7 (9.0)	1084.1 (105.8)	<0.001
Number of times planted	count	2.2 (0.1)	1.2 (0.1)	<0.001
EIQ (ecosystem)	score	3192.1 (255.4)	2967.2 (173.9)	<0.001
P fertilizer (synthetic)	kg P ha^{-1}	101.6 (7.3)	75.2 (3)	0.002
Ecklonia maxima extract	l ha^{-1}	1.1 (0.4)	0.0 (0.0)	0.009
Soil texture				
Clay (0-15 cm)	%	12.2 (1.4)	15.8 (0.5)	0.022
Clay (15-30 cm)	%	12.7 (1.7)	18.4 (0.6)	0.002
Silt (30-45 cm)	%	4.2 (0.5)	7.7 (0.3)	<0.001
Clay (30-45 cm)	%	14.8 (2)	23.3 (1.3)	<0.001
Sand (30-45 cm)	%	79.6 (2.1)	68.9 (1.2)	<0.001
Soil chemistry				
K	mg kg^{-1}	176.2 (27.5)	236.4 (18.1)	0.033
Ca	mg kg^{-1}	643.5 (61)	1091.3 (81.7)	<0.001
Na	mg kg^{-1}	9.1 (0.4)	19.4 (1.5)	<0.001
CEC	cmol(+) kg^{-1}	5.2 (0.5)	7.9 (0.6)	0.001
Ca	% bs	62.3 (0.9)	68.4 (0.7)	<0.001
Mg	% bs	28.1 (1.3)	22.8 (1.1)	0.001
Na	% bs	0.9 (0.1)	1.1 (0.1)	0.016
Ca:Mg	ratio	3.9 (0.2)	5.2 (0.3)	<0.000

[a] Only significant and meaningful differences ($\alpha = 0.05$) are reported; [b] T-test (unequal variance)

In comparison with the early and optimum planting times, the interactions between biotic and abiotic variables, and its association with high quality yield, were less intuitive or explainable. This data subset was substantially smaller than the other two, and the number of entries in each scenario was low (n ranged from 7 to 46). Thus, the overall size of the data subset might have reduced the power of CART analysis, thus making it difficult to explain variation in high quality yield in the late planting time.

4.4 Discussion

4.4.1 The relevance of synthetic pesticides

The Environmental Impact Quotient (EIQ) developed by Kovach et al. (1992) is a user-friendly, comprehensive, and regularly updated pesticide scoring system. The EIQ system was useful for exploring the relative ecological impact of the pest and disease control programs used in other tomato production systems (Clark et al. 1998, Buess et al. 2004). The range of cumulative pesticide usage (biocides and insecticides) by the South African tomato producers was comparable to international trends (Clark et al. 1998, Poudel et al. 2001, Buess et al. 2004).

Synthetic pesticides maintain current food production rates in the face of mounting disease pressure problems and are expected to remain important in the face of global climate change (Cooper and Dobson 2007, Koleva and Schneider 2009, Hillocks 2012, Thorburn 2014). The tomato crop is susceptible to a wide range of pests and diseases. Tomato production will decrease by 40-77% if key fungicides and insecticides are prohibited, with the fresh-market tomato industry being the most vulnerable to severe economic loss (Davis et al. 1996, Zalom 2003). The results of this study confirm these observations. In the early and optimum planting times, where synthetic pesticides were not consistently used, the loss of total and high quality yields ranged from 24-67%. In the optimum planting time, when the climate was very conducive for very high total and quality yields, the use of pesticides with a high ecosystem impact ensured high crop productivity.

However, the drawback of the excessive use of synthetic pesticides was also observed in this study. For the optimum planting time, use of pesticides with an excessive impact on the worker was associated with a 27% decline in total yield. The synthetic remedies were used curatively, possibly in an attempt to arrest the spread of a pest or disease in affected fields. Very few curative management options are available to tomato growers once crops are infected with bacterial, fungal or viral diseases. For this reason, preventive control programs are more cost-effective in the end and effectively prevent significant and widespread crop losses due to pests and diseases.

4.4.2 The feasibility of organic pest control

The detrimental effects of soil fumigants on the soil ecosystem are known and efforts are underway to develop alternatives solutions to the problem of disease-infested soils (Bloem and Mizel 2000). The tomato producers of the Lowveld production region relied heavily on nematode-resistant rootstocks for effective nematode control. Although these tomato producers allegedly developed an organic replacement for conventional fumigants (Hiten et al. 2011, Daneel 2014), inconsistent performance and development challenges prevented widespread implementation of the remedy.

The results of this study demonstrate that several of the organic pest control remedies, the fermented extracts of aloe, garlic/neem, lemon and even inorganic silica, proved to be potential replacements of or adjuncts to existing synthetic pesticide technologies. Unfortunately, but predictably, these fermented plant extracts were associated with yield reduction (also observed by Pelinganga et al. 2011). As with the synthetic pesticides, excessive use of these plant-derived extracts was associated with yield reduction in several instances in this study based on the CART analysis results. Clearly, credible research is needed to facilitate the development and implementation of effective on-farm produced organic pesticides.

4.4.3 The importance of synthetic fertilizers

At first glance, the South African 'nature-friendly' tomato production system had strong characteristics of high-input conventional tomato production systems because of the heavy reliance on synthetic fertilizers. The synthetic nitrogen fertilization rates of 200-300 kg N ha^{-1} were beyond the 75th percentile of rates reported elsewhere for similar tomato production systems (see Chapter 1, Table 1.3). Successful tomato yield outcomes relied on the effective application and timing of synthetic fertilization. In this study, for the early planting time, high quality yield nearly doubled when the K:N ratio was larger than 1.8. For the late planting time, high quality yield increased nearly two-fold when the N:P ratio remained below 3. Despite these observations, there was no clear correlation or association between fertilization and total yield. Such correlations may not be observed in commercial production conditions due to the vast array of additional factors that may influence total and high quality yield.

A common misperception about fertilizers is the alleged association with yield decline and the destruction of the soil resource (Vanlauwe and Giller 2006). Soil organic matter stabilization required the addition of macronutrients (Kirkby et al. 2014). Crop root development increased soil organic matter due to root particle turnover or exudation (Costa 2012). Thus, N addition could sequester carbon and so *increase* soil organic matter – several studies confirmed this (Alvarez 2005, Vanlauwe and Giller 2006, Tong et al. 2014), but not for some conventional farming systems (Küstermann et al. 2010, Maltas et al. 2013). Fertilizers improved root development and crop nutrient use efficiency, thereby reducing the ecological impact of fertilization (Castellanos et al. 2013, Nash et al. 2013). Fertilizers augmented biological nutrient cycling processes that occurred in the rhizosphere (Shen et al. 2013b). For example, when combining fertilizer and organic N sources, more of the synthetic N was immobilized over the short-term than the quantity of organic N lost via decomposition (Gentile et al. 2013). However, despite these benefits, synthetic fertilizers did not have the organic bulk that was required for forming soil aggregates. Thus, any conventional farming operation could benefit from an organic soil/crop management component.

4.4.4 The dominant effect of climate on crop productivity

This study confirmed the importance of climate variation on tomato yield and quality. Within the early and optimum planting windows, tomato yield was sensitive to crop management, soil quality, and climate extremes. Tomato quality was very sensitive to climate variation in each planting window. Yield and quality variation in the late planting window were influenced primarily by climate variation.

The major climate variables associated with yield or quality variation were temperature, solar radiation, humidity, wind speed, and rainfall (see Chapter 3). The temperature-related stressors and relative humidity affected the tomato crop during the flowering and fruit set stages of development (Charles and Harris 1972, Levy et al. 1978, Bakker 1990, Holder and Cockshull 1990, El-Abd and El-Beltagy 1996, Adams et al. 2001, Lobell et al. 2007, Xu et al. 2007). Humidity also contributed to the onset and development of above-ground diseases associated with microorganisms and insects (Yunis et al. 1980, Baptista et al. 2008). The tomato is notorious for its pollination problems (Hanna 1999), which explained the importance of windspeed and its effect on air circulation within the crop canopy as yield-limiting or –enhancing climate variable in this study.

The tomato is very sensitive to water stress (Alvino et al. 1990, Dadomo 1994, Colla et al. 2000, Hanson et al. 2000) and excessive rainfall was associated with yield reduction in some cases during the study period. The presence of excessive levels of organic matter in soils increase crop susceptibility to water stress and is associated with yield decreases in tomato (El-Beltagy et al. 1986, Argerich et al. 1999). High levels of organic matter can reduce the porosity of soils over the long term (Papadopoulos et al. 2014), thereby increasing the crop’s susceptibility to water logging stress. This effect is compounded in heavy soils because the water is trapped in the organo-mineral complex, possibly limiting its availability to the roots. Consequently, the tomato grower has to expertly manage two water-related challenges: irrigate more frequently to provide available water, nutrients and avoid drying out the soils while avoiding the risk of saturating the root zone with moisture that cannot drain through gravitational force. The South African tomato producers used indeterminate cultivars, which meant flowering and fruit set occurred continuously for a 15-week period until the final harvest. Thus the crop was vulnerable to yield-limiting climate variation for the greater part of the crop's lifespan.

4.4.5 The role of benign soil microbiology in crop production

The prudent combination of both synthetic and organic nutrient sources may be advantageous for tomato production. For example, for the early planting time, the difference between low and high yield hinged on the soil potassium content: the productivity of low-potassium soils ($\leq$155 mg kg^{-1}) increased 27% when >13.2 kg ai ha^{-1} of commercial humic acid was applied during the production season. The contribution of humic acid formulations to crop production remains a contentious issue. Several studies recently documented the effect of humic acid formulations on tomato growth and yield (Dursun et al. 2013, Hussein et al. 2015, Olivares et al. 2015). However, with a K content of 15% (and assuming 100% solubility), and given the application rates of 2.9 - 7.1 kg K ha^{-1} (the range of K-humate® used in scenario 2, Fig. 4.1), the commercial humic acid formulation simply could not have provided any meaningful K fertilizer effect. The apparent benefits of humic acids include improved fertilizer use efficiency, improved root development, direct impacts on crop metabolism and the stimulation of microbial activity (Canellas et al. 2015, Rose et al. 2015) – these effects were not directly measured in this study.

However, this was the only example where organic technologies for managing soil organic matter or the soil biology component made any statistical difference in yield. This was a disappointing result, given the sustained and increased use of compost, compost tea, and Effective Microorganisms® over the eight-year period. Despite following a 'nature-friendly' production philosophy, the use of synthetic fertilizers and pesticides often exceeded the industry norm (see Chapter 1), nor did it decline over time as the agro-ecosystem responded to organic management. Although these South African tomato producers were determined to manage the soil organic matter component through the consistent application of compost, the consistent use of synthetic pesticides and herbicides may explain why biological nutrient cycling was not as effective as anticipated (Horswell et al. 2014). More research is needed to understand the interactions between biological nutrient cycling (and disease suppression) and synthetic crop nutrition and protection technologies used at the farm level.

4.4.6 Inconsistent CART analysis results

The challenges of interpreting CART analysis results were highlighted and discussed in the previous chapter (see sections 3.4.1 and 3.4.4). In this chapter CART analysis again produced several apparently illogical or inconsistent findings; these will be explored below.

Potassium undeniably is a critical component of any vegetable fertilization program. CART analysis indicated that tomato yield was suppressed in soils with a K content exceeding 155 mg kg^{-1}, provided the level of adjuvants used in the pest control programmes did not exceed 79 kg ai ha^{-1} (scenario 3, Fig. 4.1). When reviewing CART analysis results, it is important to guard against outlier scenarios that may be of minor importance in the wider perspective. For example, the use of such high levels of adjuvants was reported for only 10 cultivation events (out of a total of 362 cultivation events); that scenario represented 2.8% of the dataset and can be considered an outlier not requiring serious attention (unless specific questions about the pest control programme must be answered). Furthermore, tomatoes are less responsive to K fertilization in soils with high levels of K (Hartz et al. 2001). Indeed, in South Africa, Van Biljon et al. (2008) found that maize was least responsive to K fertilization at a soil K level of 190 mg kg^{-1}. Excessive available potassium restricts the uptake of calcium and magnesium, causing nutrition disorders and ultimately reduced yield of tomatoes (Kabu and Toop 1970, Bar-Tal and Pressman 1996). High levels of potassium in the nutrient solution of greenhouse tomatoes cause delayed harvesting (Adams and Grimmett 1985). Thus, for the early planting time, inexpert K fertilization of an unresponsive soil could extend harvesting into late autumn and winter, exposing the crop to yield-limiting temperatures. Finally, potassium uptake efficiency differs between cultivars (Chen and Gabelman 1995). In this study a single cultivar was used in 95% of the cultivation events (data not shown) and therefore cannot explain the variation in yield based on cultivar differences. In summary, the aforementioned factors provide reasonable explanations for the lower tomato yield reported for high K soils when planted in the early planting time.

Interpreting contradictory or inexplicable results in the interdisciplinary research context can be challenging. For example, specific climate, soil and crop management variables interact, apparently, to explain variation in tomato quality during the early planting time (Fig. 4.2). The tomato growers experimented with bat and bird guano for a limited period of time in 2005 and 2006. The growers observed significant yield and quality problems and soon ceased application of any guano products. This explains the low number of observations for scenarios 5-8 (Fig 4.2). Nevertheless, the results confirmed the importance of adequate weed control as a means to maintain tomato yield (scenarios 7 and 8, Fig. 4.2, Weaver and Tan 1983, Clark et al. 1999). Furthermore, it confirmed the negative impact on tomato quality of high atmospheric moisture content, measured as the dewpoint (scenarios 5 and 6, Fig. 4.2; see also Chapter 3, section 3.4.4.3). If we consider the interactions reported for scenario 1 to 4 in Fig. 4.2, there was no statistical difference in HQY between scenario 1 and 4 ($p > 0.10$, Kruskal-Wallis test). Scenario 1 contains the majority of the cultivation events (65%) in node number 2; the remaining scenarios must therefore be interpreted with care because more splits and fewer entries per split are involved. For example, the contribution of the fermented plant extracts to explain variation in tomato quality (scenarios 1-4, Fig. 4.2) cannot be verified in the context of this dataset. The importance of adequate evaporative demand to explain tomato yield variation was demonstrated again (see Chapter 3, section 3.4.4.2), but this has to be implied based on accepted agronomic principles and the assumption the growers were able to match irrigation supply with the atmospheric evaporative demand. Thus, far from providing clear-cut empirical evidence, the outcomes reported here should lead to replicated pot and field trials to follow up on the more challenging, yet potentially useful, CART analysis results. For this reason, CART analysis may serve as a hypothesis generating tool when dealing with complex interdisciplinary projects.

Multivariate statistical techniques aim to extract the factors (or combinations thereof) that explain the maximum amount of variation in the dataset. CART analysis is not different in this aspect. Hence, the importance of the status quo is not emphasized, but rather the outlier or extraordinary situations receive emphasis. For example, during the late planting time, variation in tomato quality hinged on the duration of the fallow period: high quality yield was substantially higher when fallow periods between planting events lasted < 333 weeks and vice versa (scenarios 6 and 7, Fig. 4.6). Socio-economic pressure and climate change make it harder for growers to own (and abandon) large tracts of land in lieu of crop production demands and challenges. We will be significantly closer to realizing true sustainable intensification if growers can farm the same soil for longer periods of time without a decline in soil and crop productivity. The CART analysis results reported in scenarios 6 and 7 in Fig. 4.6 may potentially provide that insight. However, the CART analysis procedure was unable to provide any additional discriminatory guidelines other than the climate events both scenarios share in the superior nodes of the hierarchy. Univariate statistical comparisons of the variables in the dataset for the short and long fallow periods provided several statistically significant differences (Table 4.2). The fields with the shorter fallow periods received more synthetic P nutrients and synthetic pest- and disease control chemicals with a higher cumulative impact on the ecosystem based on the EIQ scoring methodology. Several studies described the impact of the extract of *Ecklonia maxima* on the growth, development and resistance to biotic and abiotic factors of a range of crops, including tomatoes (Featonby-Smith and Van Staden 1983, Crouch and van Staden 1992, Khan et al. 2009, Sharma et al. 2014). Furthermore, the fields with the long fallow periods had higher clay content, especially at the deeper levels, and this possibly created challenges for the growers related to irrigation, water drainage after rainfall events and root health problems (Bao et al. 2013, De Pascale et al. 2016). Although these soils had a higher CEC, the level of key macro elements, notably K and Na, were higher which may have created challenges for the growers related to poor crop responsiveness to fertilizer addition (especially K) and soil salinity (De Pascale et al. 2012, Bar-Yosef et al. 2015). Post hoc PCA (data not shown) confirmed that high quality tomato yield was positively associated with a high sand content in the soil profile and opposed by the soil clay content (at 15-45 cm) and the levels of the macro elements (except the percentage of Mg). In this example, the CART analysis results did not provide a mechanistic explanation for how the duration of the fallow period influenced the variation in tomato yield and quality. The procedure identified a suitable data subset that could be further analyzed and plausible reasons for the variation in tomato quality were extracted from Table 4.2. However, the example demonstrated the CART analysis procedure was not immune to the 'false correlation' problem and CART analysis results must be carefully scrutinized by the researcher, reviewer and reader.

4.5 Conclusions

Complex interactions between biotic and abiotic variables influenced tomato yield and quality. The tomato producers of the Lowveld production region in South Africa used a range of organic technologies in addition to synthetic fertilizer and pest/disease control remedies. The fermented plant extracts made from aloe, garlic, and neem were associated with high yield outcomes in the early planting time. However, the use of imported bat and bird guano had clear negative effects on tomato yield, as did the excessive use of the fermented plant extracts. However, the onus remained on the producer to create an agro-ecosystem that did not encourage pest/disease problems and thus necessitated the use of high impact pesticides. Selecting the proper planting window, use of disease-resistant genetic material, intelligent crop rotation and fallow management, and the balanced use of synthetic and organic crop management technologies were keystones of sustainable, open field commercial tomato production. The findings of this study will benefit policy development in support of sustainable vegetable production in the rural areas of Southern Africa.

The example set by these tomato producers is commendable because they actively and deliberately managed the soil microbiological component despite the absence of clear agronomic benefits by the use of these organic technologies. These farmers acknowledged the potential ecological damage done by their unavoidable reliance on synthetic pest and disease control remedies, especially when disease-conducive climate conditions prevailed. Yet they attempted to replenish or restore the soil microbiological component by means of compost, compost tea and Effective Microorganisms® after synthetic pesticides had been used. The use of an appropriate soil biology metric can validate the usefulness of the use of such soil biology management technologies. The usefulness of three soil biology metrics in support of sustainable tomato production will be explored in the next three chapters (Chapters 5-7).

CHAPTER 5

EXPLORING THE RELATIONSHIP BETWEEN MICROSCOPY-BASED SOIL BIOLOGY MEASUREMENTS AND TOMATO YIELD IN SOUTH AFRICA

Abstract

Soil biology management is an important aspect of sustainable agriculture. The use of appropriate soil biology metrics can facilitate soil biology management at field scale. Tis study aimed to investigate, 1) whether a commercially available, microscope-based soil biology metric was useful for describing a soil management gradient in the order, natural > pre-plant (tilled) > cultivated > fallow, and 2) whether there was a correlation between the measured soil biology variables and tomato crop productivity. The following measurements were made: total and active fungi and bacteria biomass, fungal hyphal diameter, fungi and bacteria biomass ratios, and soil protozoa numbers. Results indicated that the soil biology metric was sensitive for documenting the impact of soil management that involved tillage. The total fungal biomass was significantly lower and the number of ciliates was significantly higher in the pre-plant soils, but there was no difference between natural, cultivated and fallow soils for either the fungal biomass or the number of ciliates. The total fungal biomass responded negatively to the physical disruption of the soil caused by tillage, whereas the number of ciliates responded positively to the flush of microbial activity associated with the decomposition of freshly incorporated organic matter following tillage. Principal component analysis and multivariate regression analysis indicated that none of the soil biology variables adequately explained tomato yield variation, regardless of sampling before or during crop production (R^2 of 0.345 and 0.114 respectively). The microscope-based soil biology metric has several shortcomings and limit the usefulness of this metric as soil food web management decision-support tool for tomato growers.

Keywords: Bacteria, Ciliates, Soil food web, Total fungi

5.1 Introduction

The tomato is an important vegetable with a range of reported nutritional and health benefits. It is cultivated everywhere on Earth except Antarctica. Worldwide, tomato production requires intensive use of fertilizers, synthetic pesticides, tillage, energy and labour in order to provide high-value marketable produce (Canakci and Akinci 2006, Zalom 2013, Soto et al. 2015). Hence, there is a need to improve the sustainability of tomato production systems in general. The importance of biologically active soils to the overall sustainability of commercial tomato production systems remains unclear. In the present time there is no shortage of information about the importance of chemical and physical attributes to the effective functioning of soils and the resultant impact on tomato crop productivity. The importance of the plant pathogenic aspect of the soil biological component is well-appreciated and remains an active research area for all crops, especially the tomato (van Bruggen et al. 2015, Wu et al. 2015).

A host of soil health metrics was used in several studies to compare the impact of conventional and organic tomato production systems (e.g., Ferris et al. 2004, Tu et al. 2006, Liu et al. 2007b, DuPont et al. 2009, Buyer et al. 2010, Hernandez et al. 2014). However, very few of these studies, apart from those focusing on plant disease, correlated the soil biological results with tomato yield. Tomato yield and quality are influenced by a complex set of biotic and abiotic variables. Total yield is realized by harvesting large quantities of the right size and mass of fruit per hectare. Total yield is primarily a function of suitable climate conditions, the absence of severely debilitating pests or diseases, optimum irrigation, optimum crop nutrition, and the use of an appropriate cultivar. The presence of disease-causing organisms and the effective control thereof remain an important yield-limiting factor in the sustainable tomato production context. Structural and functional components of the soil food web have a potential role to play in terms of biological nutrient cycling, improved crop health (induced resistance, plant growth promotion), and biological disease suppression.

The soil food web is structurally and functionally complex. The soil food web encompasses the biomass, activities and interactions of all the biotic components in soils, from the soil viruses, bacteria, fungi, protozoans, nematodes, mites and the higher order insects (Buée et al. 2009). This presents a formidable analytical challenge to crop producers who wish to manage specific soil food web components in response to laboratory test results. Choosing the appropriate soil biology metric depends on the crop producer’s management objectives. However, production of a low-value crop or tough economic conditions means crop producers do not invest readily in routine soil biology testing. Therefore, the need exists for easily interpretable and cost-effective soil biology metrics to verify the impact of the soil biology management interventions implemented by crop producers.

A range of potential biological indicators are available to crop producers for testing under field conditions (Pulleman et al. 2012, Riches et al. 2013). Standard methods are available for measuring the general microbial activity and biomass through molecular, bio/chemical or metabolic means. Testing for soil macrobes (e.g., protozoa, nematodes, mites and more) presents additional higher-order information on soil food web functioning and stability. A polyphasic approach to soil biology testing describes complementary soil food web functions and interactions. One such method is based on the measurement of the total and active fungi and bacteria biomass, as well as enumeration of soil protozoans according to basic morphological groups (Ingham et al. 1985, 1986). This metric provides a basic overview of the condition of the soil food web being studied based on the actual biomass results and ratios between the key components analysed.

Literature contains many reports of how this specific set of tests was used to explore microbial population dynamics in ecological gradients (Seiter et al. 1999, Boulton et al. 2003, Setälä and McLean 2004, Hart 2006, Meiman et al. 2006, Fisk et al. 2010). The biology indicators were useful in high organic matter soils (Griffiths et al. 1997, Wagner et al. 1997, Savin et al. 2004) and for documenting the impact of severe land management practices such as land levelling/tillage (Lowell and Klein 2001, Brye et al. 2006, Rygiewicz et al. 2010), wastewater flooding of soils (Amador et al. 2006), heavy metal contamination (Kuperman et al. 1998) and pesticide applications (Coleman et al. 1994, Ingham et al. 1995, Ingham and Thies 1996, Smith et al. 2000, Liu et al. 2007b). Despite this track record in ecology, only one report could be found in scientific literature where the test methods were applied to commercial agricultural operations and correlated with crop yield (Van Antwerpen et al. 2007).

It is reasonable to expect crop producers to use soil biology metrics to support decision-making regarding management of the soil biology component in a way similar to how soil nutrient content is routinely measured and managed. The largest commercial tomato producer in South Africa implemented a nature-friendly production system since 2003. This particular example of commercial-scale eco-agriculture was described in literature, albeit superficially (Uphoff and Thies 2011). Managing the soil microbiological content and diversity by means of compost, manures, compost tea, and Effective Microorganisms® formed an important part of this tomato production system. The objectives of this study were to evaluate the microscope-based soil biology metric in terms of: 1) its sensitivity to changes in soil management and, 2) whether there was a link between the soil microbiology results and tomato crop productivity.

5.2 Materials and methods

5.2.1 Tomato production region

A detailed description of the production region appears in Chapter 3 (section 3.2.1).

5.2.2 Tomato production system

A detailed description of the production system appears in Chapter 3 (section 3.2.2).

5.2.3 Sampling strategy

A survey of tomato production units was conducted from 2005 to 2009. Soil samples were collected randomly for soil biology testing by producers and agronomists. Soil samples were taken at 0-15 cm depth with an auger from three-hectare fields because yield data was recorded by producers at that scale. Samples reached the laboratory within 24 hours and were processed immediately. The majority of samples were taken during the growing season (referred to as 'cultivated soil') (50 samples; 48%), whereas the remaining samples were taken when field clearing and ridging activities commenced (referred to as 'pre-plant soil') (28 samples, 27 %), or during the fallow period (referred to as 'fallow soil') that followed the cultivation event (11 samples, 10 %). Finally, samples were taken from undisturbed sites (referred to as 'natural soil') in the same bioregion (16 samples, 15 %), giving a total of 105 samples. The basic characteristics of the sampled sites are given in Table 5.1.

TABLE 5.1: Description of sample sites according to disturbance levels and soil quality variables in the Lowveld tomato production region of South Africa (mean ± standard error)

Soil disturbance:	**Natural**	**Pre-plant**	**Cultivated**	**Fallow**
Description	Undisturbed soils covered by natural vegetation	Disturbed soils (freshly tilled, bare soil)	Disturbed soils (in production)	Recovering from disturbance
Number of samples	16	28	50	11
pH (KCl)	nd[a]	5.40 ± 0.09	5.70 ± 0.08	nd
Clay (%)	nd	10.5 ± 0.6	13.1 ± 0.7	nd
Silt (%)	nd	8.6 ± 0.4	8.3 ± 0.3	nd
Sand (%)	nd	80.8 ± 0.8	78.7 ± 0.8	nd

[a]. nd: not determined

The economic sustainability of commercial tomato production in South Africa depended on all-year supply of high quality produce. For this reason, yield information is reported as t ha^{-1} of cumulative total yield (TY), which included unmarketable fruit, and high quality yield (HQY), which included first and select grade yields only.

5.2.4 Soil biology analyses

All soil biology analyses were performed by the Soil Foodweb Institute of South Africa (SFISA) laboratory located in the Limpopo Province. The methods relied on the microscope as primary instrument for making measurements of microbial numbers by means of phase contrast light microscopy and epifluorescence microscopy. Active bacteria (AB) and fungi (AF) were determined by epifluorescence microscopy using the modified agar-film technique of Ingham and Klein (1984a). Total fungi (TF) were determined by light microscopy using the agar-film technique (Ingham and Klein 1984b). Total bacteria (TB) were determined by epifluorescence microscopy using the fluorescein isothiocyanate (FITC) staining technique of Babiuk and Paul (1970). The hyphal diameter (HD) of all fungi was measured with a counting grid and the number reported described the median hyphal diameter observed in 90 microscope fields per sample. The mean hyphal and bacterial diameters were used to convert fungal hyphal lengths and bacterial counts to biomass according to the density conversion factors of Van Veen and Paul (1979).

Protozoans were observed by means of phase contrast light microscopy according to the most probable number (MPN) method of Ingham (1994) and classified as flagellates (F), amoebae (A), or ciliates (Cil) - only the naked form of soil amoebae are reported.

All soil biology results are reported on a per gram dry soil basis as μg g^{-1} for bacteria and fungi, and numbers g^{-1} for protozoans.

5.2.5 Soil physical and chemical analyses

Soil physical properties were analysed according to standard methods (The Non-affiliated Soil Analyses Work Committee, 1990) by a commercial soil testing laboratory (Agrilab, Tzaneen, South Africa). Sand, silt, and clay content were determined with the hydrometer method on samples taken at 15 cm depth. Soil was air dried, sieved through a 2 mm sieve for determination of the stone fraction (weight/weight basis) and analysed for pH (1.0 M KCl). Soil P (Bray I) was extracted at pH = 2.6 with 0.025M HCl and 0.03M NH_4F. Total extractable cations, namely K, Ca, Mg and Na were extracted at pH = 7 with 0.2 M ammonium acetate. Soil K, Ca, Mg and Na content results are reported as exchangeable (mg kg^{-1}) and base saturation basis (%).

5.2.6 Statistical procedures

Uni- and multivariate statistics were performed with PAST (PAleontological STatistics version 2.07b; Hammer et al. 2001). Outliers were identified by the interquartile range method and substituted by winsorization. Data transformations were performed prior to data analysis: log10(x+1) (for protozoan counts and crop management variables) and arcsin(√x) (for proportions). Statistical analyses were performed with transformed data, but actual data are shown in tables. Statistical significance was established with ANOVA and *post hoc* means separation with Tukey's Honestly Significant Difference (HSD) test. Principal Component Analysis (PCA) of the correlation matrix was used to explore the interactions among variables and tomato yield; variables with correlations of $r = |0.4|$ were retained for further analysis. Linear regression was performed to create quantitative yield prediction models from the PCA results. Soil biology samples were taken from either prepared soils prior to planting (28 samples) or from cultivated soils after planting (50 samples); statistical analyses were performed separately on each dataset. In all cases statistical significance was established at $\alpha = 0.05$.

5.3 Results

5.3.1 Soil management

In this study, soil preparation for tomato production entailed soil disturbance by mouldboard ploughing, ridge tillage, the incorporation of exogenous organic matter inside the ridges and decomposition of natural vegetation destroyed by tillage. This activity exerted the greatest influence on the analyzed soil biology variables. Total fungal biomass, AF:TF ratio, hyphal diameter and the numbers of ciliates were useful indicators of change in soil management (Table 5.2).

TABLE 5.2: Soil biology variables and change in soil management associated with open field tomato production[a]

Variables[b]	**Units**	**Soil management**				**ANOVA**[c]		
		Natural	**Pre-plant**	**Cultivated**	**Fallow**	**F-value**	**P-value**	**Tukey's LSD**
Bacteria and fungi:								
AB	$\mu g\ g^{-1}$	20.2	14.8	17.9	13	1.861	ns	na
TB	$\mu g\ g^{-1}$	433.1	826.8	721.4	690.4	2.422	ns	na
AF	$\mu g\ g^{-1}$	2.2	3.8	2.9	2.2	0.952	ns	na
TF	$\mu g\ g^{-1}$	128.6a	39.4b	98.7a	130.1a	5.488	0.001	70.4
TF:TB	Ratio	0.32	0.22	0.25	0.18	0.526	ns	na
AF:AB	Ratio	0.12	0.32	0.28	0.13	1.069	ns	na
AF:TF	Ratio	0.03b	0.34a	0.08b	0.03b	15.26	<0.001	0.23
AB:TB	Ratio	0.05	0.08	0.05	0.03	0.714	ns	na
HD	mm	2.5a	1.4b	2.5a	2.7a	16.54	<0.001	0.59
Protozoa:								
F	numbers g^{-1}	33 522.5	11 0578.1	102 062.1	87 780.0	1.025	ns	na
A	numbers g^{-1}	1 078.7	2 070.4	2 709.3	11.1	8.539	ns	na
Cil	numbers g^{-1}	3 314.3b	19 391.7a	4 598.9b	317.2b	12.93	<0.001	9.3

[a.] Means in a row followed by the same letter do not differ significantly at $P \leq 0.05$; [b.] A: amoebae; AB: active bacteria; AF: active fungi; Cil: ciliates; F: flagellates; HD: hyphal diameter; TB: total bacteria; TF: total fungi; [c.] LSD: least significant difference; ns: not significant ($P > 0.05$);

The total fungal biomass was significantly lower in the disturbed soils than the undisturbed soils (natural, cultivated and fallow soils). Although the active fungal biomass did not differ significantly between the various soil management types, the lower total fungal biomass ensured that the AF:TF ratio was significantly higher during the pre-plant stage. The number of ciliates was significantly higher in the pre-plant and cultivated soils (Table 5.2). Despite the numerical superiority of the flagellates, soil management did not impact significantly on their abundance. Although tomato cultivation requires regular synthetic fertilizer and pesticide applications, no differences in soil biology variables were observed between natural and cultivated soils as well as between cultivated and fallow soils.

5.3.2 Soil biology and tomato yield

Tomato production in South Africa is economically sustainable provided high total and quality yields are achieved consistently. Crop producers will value soil biology testing if there is an association with crop yield. For the samples taken during the soil preparation stage, tomato yield was associated with the fifth principal component (Table 5.3).

TABLE 5.3: Principal component analysis results of the pre-plant soils dataset

PCA results	
Principal component	5
Eigen value	1.936
Variation	7.17%
Variables[a]	**Correlation with PC**
Tomato yield	-0.805
TF:TB	0.499
AF:AB	0.436
AB:TB	0.489

[a] AB:TB = active bacteria/total bacteria; AF:AB = active fungi/active bacteria; TF:TB = total fungi/total bacteria

Three soil biology variables were correlated with tomato yield in PC5: the ratios of TF:TB, AF:AB and AB:TB. These variables were used to construct a predictive tomato yield model by means of regression analysis (Table 5.4). The predictive power of the resulting model was not satisfactory at $R^2 = 0.345$ (Fig. 5.1).

TABLE 5.4: Descriptive statistics of the linear regression model for predicting the tomato yield based on the biological, physical and chemical characteristics of the pre-plant soils

Linear model components[a]	Coefficient	Standard error	R^2
Constant	100.8	3.8	
TF:TB	-30.6	18.5	0.321
AF:AB	-4.1	5.2	0.009
AB:TB	17.4	37.1	0.255

[a] AB:TB = active bacteria/total bacteria; AF:AB = active fungi/active bacteria; TF:TB = total fungi/total bacteria

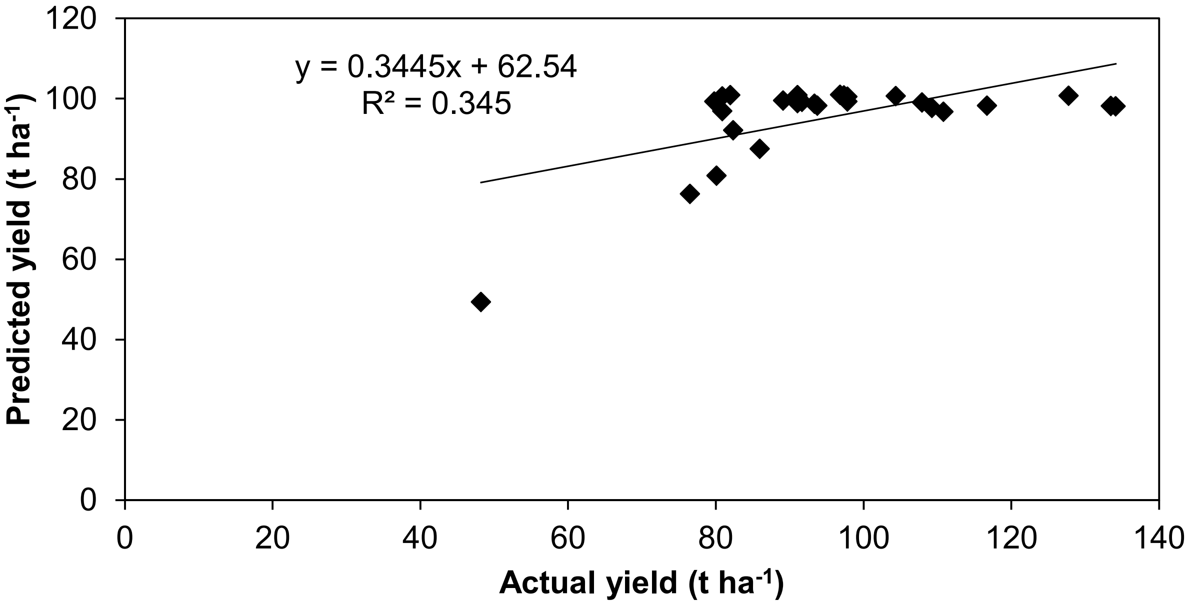


FIG. 5.1: Tomato yield prediction based on the biological and chemical characteristics of pre-plant soils

For the samples taken during the tomato production stage (cultivated soils), tomato yield was associated with the fourth principal component (Table 5.5).

TABLE 5.5: Principal component analysis results of the cultivated soils dataset

PCA results	
PC	4
Eigen value	2.355
Variation	8.72%
Variables	**Correlation with PC**
Tomato yield	0.435
Total fungal biomass	0.470
Calcium (%)	-0.600
Magnesium (%)	0.549

One soil biology and two soil chemistry variables were correlated with tomato yield in PC4: total fungal biomass, calcium (%) and magnesium (%). These variables were used to construct a predictive tomato yield model by means of regression analysis (Table 5.6). The predictive power of the resulting model was not satisfactory at $R^2 = 0.114$ (Fig. 5.2).

TABLE 5.6: Descriptive statistics of the linear regression model for predicting tomato yield based on the biological, physical and chemical characteristics of the cultivated soils

Linear model components	**Coefficient**	**Standard error**	**R^2**
Constant	47.948	100.6	
Total fungal biomass	0.015	0.036	0.000
Calcium (%)	0.472	114.6	0.093
Magnesium (%)	109.2	104.3	0.111

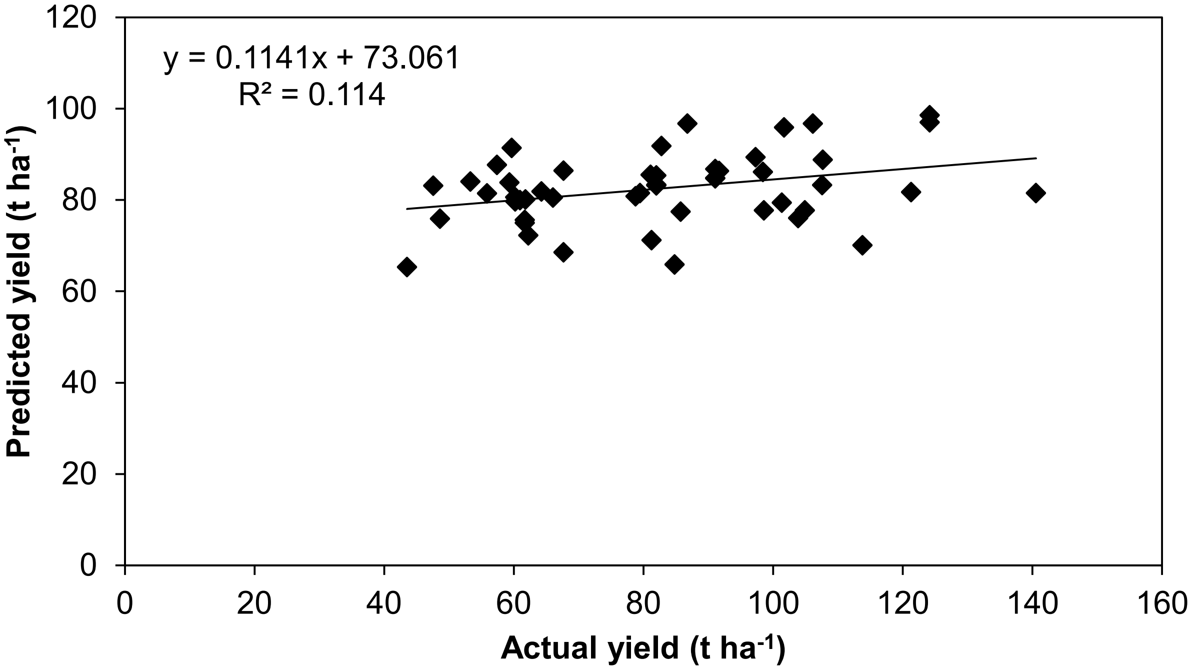


FIG. 5.2: Tomato yield prediction based on the biological and chemical characteristics of the cultivated soils

5.4 Discussion

5.4.1 Significance of the study

The study and management of the soil biology component of cultivated soils are important aspects of sustainable agriculture. It is reasonable to expect producers to use soil biology metrics in order to support decision-making regarding management of soil biology in a way similar to how soil nutrient content is routinely measured and managed. This is a workable proposal provided the soil biology metric is sensitive to soil and crop management, scientifically relevant, doable in a laboratory on a large scale and cost-effective (Doran and Zeiss 2000). Although this specific set of microscope-based soil biology tests are cited in many research papers, this study provided much-needed feedback to the greater agriculture and applied microbiology communities on the strengths and limitations of this commercially-available soil biology metric.

5.4.2 Soil management

Ridge tillage is commonly observed in tomato production systems. Although reduced tillage is successful for commercial tomato production in general, ridge-tillage provides soil quality, nutrient management and water run-off management benefits (Stirzaker et al. 1989, Creamer et al. 1996, Midmore et al. 1997, Sainju et al. 2000, Montemurro et al. 2009, Mujuru et al. 2013). The results reported here demonstrated that the microscope-based soil biology metrics used in this study were sensitive to detect changes in soil management that involved physical disturbance of the soil; this was in agreement with previous studies using the same metric (Lowell and Klein 2001, Brye et al. 2006, Liu et al. 2007b, Entry et al. 2008, Rygiewicz et al. 2010). The total fungal biomass was very sensitive to soil disturbance and negatively affected by repeated short-term ploughing while total bacterial biomass increased (Liu et al. 2007b, Entry et al. 2008). During the pre-plant stage, ploughing destroyed delicate fungal hyphae, but the destruction of macro-aggregates exposed previously shielded soil organic matter to bacterial decomposers (Govaerts et al. 2009). Furthermore, ploughing of grassland soils lead to the incorporation of fresh plant biomass into the soils, which further encouraged lignocellulose decomposition. Microbial predators also responded to the increase in soil microbial prey numbers – this explained the higher protozoan numbers reported for the pre-plant soils. Despite the known sensitivity of soil fungi to soil disturbance, the results from this study demonstrated that fungal biomass recovered rapidly to pre-disturbance levels during the crop production stage. However, the metric was not able to indicate if a change in the composition of the fungal population at the species or genus level occurred or not.

5.4.3 Soil biology and tomato yield

A complex combination of abiotic and biotic factors influenced tomato yield and quality. The results indicated when the fields were sampled prior to planting, the ratios of TF:TB, AF:AB and AB:TB were potential predictors of tomato quality. Total yield was positively associated with bacterially dominated soils. Plant-available nutrients are released from the microbial biomass pool during predation by soil protozoa, nematodes and other soil food web macrobes (DuPont et al. 2009, Bender and Heijden 2014). The predatory activities of nematodes were positively associated with tomato yield in several studies (Ferris et al. 2004, DuPont et al. 2009). Although similar predatory activities by protozoan and other soil food web predators was assumed to happen in the studied soils, nutrient cycling and microbial biomass turnover was not directly measured in this study. Soil and crop management influence microbial population dynamics at the genus and species level in tomato cropping systems (Liu et al. 2007ab, Buyer et al. 2010). However, the mere distinction between broad categories of soil food web components was not helpful to explain the statistical associations with tomato yield as observed in this study.

Tomato quality is dependent on favourable climatic conditions, crop management and disease-conducive climatic conditions (see Chapter 3 and 4). The association between specific soil food web components and tomato quality was likely to coincide with favourable climatic conditions or crop management interventions, especially pest- and disease-control programs. This explains why no strong associations between soil food web variables and tomato yield were observed when samples were taken during the crop production stage. The consistent use of synthetic fertilisers and pesticides may further complicate the interpretation of the biological results.

5.4.4 Limitations of the study

Concerns regarding the microscope-based soil biology metric itself complicated interpretation of these results. For example, the unspecific nature of the result – 'active bacteria' or 'number of ciliates' - prevented further hypothesizing and follow-up experimentation in order to explore the causal mechanism(s). For this reason, these microscope-based methods were supplemented with additional soil tests and advanced molecular methods in other studies (Lowell and Klein 2001, Schutter et al. 2001, Compton et al. 2004, Amador et al. 2006, Liu et al. 2007b, Van Antwerpen et al. 2007, Entry et al. 2008, Fisk et al. 2010, Shrestha et al. 2011), but this only highlighted the limitations of the microscope-based methods even further. Furthermore, microscope-based methods were prone to inter-analyst variation, over- or under-estimation of biomass, stain selectivity issues, analyst fatigue, and successful outcomes required substantial analyst experience (Frankland 1974, Paul and Johnson 1977, Bååth and Söderström 1980, Stahl et al. 1995, Schutter et al. 2001, Van Antwerpen 2005, Joergensen and Wichern 2008, Van der Wal et al. 2009). The most important criticism against the specific metric concerned the inability to discern between beneficial and plant-pathogenic fungi or bacteria – this may explain the inconsistent association of fungal and bacterial variables with tomato yield because the analyst simply did not know which fungi or bacteria were observed.

The most probable number (MPN) method used for counting soil protozoans was also criticised by several authors (Fredslund et al. 2001, Agis et al. 2007). The main problem with this method is the culturability factor which is similar to long-standing criticism of using standard microbial agar plate-count techniques in microbial ecology studies. The simple distinction between flagellates, amoebae and ciliates is not helpful other than giving an inventory of broad categories of organisms whilst no new knowledge is gained about soil biology processes involving nutrient cycling, disease suppression and related soil health concepts, a view echoed by several protist authorities (Bamforth 1995, Foissner 1999, Fredslund et al. 2001). These methodological limitations could have contributed to experimental error and might have influenced the reliability of the results.

Future work should focus on evaluating soil biology metrics that describe soil food web functionality. Specific emphasis should be placed on measuring turnover of microbial C and N. The distinction between pathogenic and benign soil food web components will be important for adequately explaining tomato yield variation. The physical and chemical characteristics of the soil matrix constrain the functioning of the soil food web. Therefore, future work should take advantage of recent advances in soil health testing (e.g., nematode community profiling and multidisciplinary soil health testing).

5.5 Conclusions

In summary, the microscope-based soil biology metrics used by the South African tomato farmers were useful for describing the impact of changes in soil management intensity, especially when tillage was involved. However, the correlation with tomato yield and quality was less robust and of limited value as decision-making tool, especially regarding biological nutrient cycling. The particular metric is unsuitable for resource-limited soil testing labs because of the requirement of highly trained and experienced analysts in addition to expensive microscope(s). Samples must reach the laboratory within hours for the successful completion of the microscope-based assays – this is a real challenge in the rural areas of Southern Africa. Nevertheless, management of the soil biology component remains vital to any sustainable agriculture philosophy and research efforts should continue to develop relevant and affordable producer-friendly soil health/quality metrics. For these reasons the second commercially available soil biology metric, nematode community profiling, was evaluated for its usefulness in the commercial tomato production context (see Chapter 6).

CHAPTER 6

NEMATODE COMMUNITY PROFILING AS A SOIL BIOLOGY MONITORING TOOL IN SUPPORT OF SUSTAINABLE TOMATO PRODUCTION[3]

Abstract

Management of the biological component of agricultural soils is a vital aspect of sustainable food production systems. There is a need for soil biology metrics that producers can use as decision support tool when it comes to managing the soil biological component of agricultural soils. The usefulness of nematode community profiling as a soil biology monitoring tool in support of a sustainable commercial-scale tomato production system in South Africa was evaluated. The objectives were to: 1) study the effects of a soil disturbance gradient on nematode communities in the tomato production region, and 2) explore the correlation between tomato crop productivity and the nematode community metrics. The enrichment index was a sensitive indicator of soil disturbance, but the structure index was not. The number and proportion of free-living and plant-parasitic nematodes increased and decreased respectively along the natural > pre-plant > cultivated soil disturbance gradient, but an increase in specific economically important plant-parasitic genera was also observed. *Helicotylenchus* spp. was sensitive to soil disturbance and might serve as soil health indicator in this tomato production region. Regression analysis indicated that a combination of variables associated with soil pH, free-living nematodes (notably the bacterivores) and specific plant-parasitic nematode genera (*Paratrichodorus* spp. and *Rotylenchus* spp.) predicted tomato yield well ($R^2 = 0.846$). Despite the useful information gleaned from the nematode community metrics regarding soil food web functioning, the importance of ecologically and economically important nematode genera was re-emphasized. The results of this study highlight an important principle regarding development of soil health metrics for tomato agroecosystems: tomato crop health may not necessarily be predicted solely by indicators of soil food web health and functioning.

Keywords: Diversity, Enrichment index, *Helicotylenchus* spp., *Paratrichodorus* spp., pH, Yield

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[3] A manuscript based on this chapter was accepted for publication in *Applied Soil Ecology* 93: 19-27 (DOI 10.1016/j.apsoil.2015.03.011)

6.1 Introduction

Management of the biological component of agricultural soils is a vital aspect of sustainable food production systems. The soil's biological component can provide several ecosystem services to the crop producer; biological nutrient cycling and biological disease suppression attract the most attention from producers and scientists. Producers wish to manage the soil biological component in the same way as they manage fertilizer and pesticide applications based on appropriate laboratory tests or on-site observations (i.e., scouting for insect pests). Not surprisingly, a wide range of soil biology metrics has been described in the literature and several have been commercialized (Pulleman et al. 2012, Riches et al. 2013). Each metric has its theoretical, procedural, and practical shortcomings. The challenge for biologists is to devise a metric that satisfies the basic requirements of scientific excellence, procedural simplicity, and agronomic relevance (Doran and Zeiss 2000). Nematode Community Profiling (NCP) by means of functional guild analyses and related indices (Yeates et al. 1993, De Goede and Bongers 1994, Ferris et al. 2001) is a promising soil biology metric that is being used increasingly to describe ecological and soil disturbance gradients.

Nematodes are ubiquitous to the soil environment. Vegetable crop producers are well-aware of the negative consequences plant-parasitic nematodes (PPNs) have on crop production. However, few producers are aware that nematode communities contain non-parasitic nematodes which may provide positive outcomes to crop production. Apart from documenting the PPN community in soil, NCP can provide insights into soil food web stability and ecological functioning. For example, nematodes contribute directly and indirectly to nitrogen cycling in soils (Anderson et al. 1983, Ferris et al. 1998, Buchan et al. 2013) and this information may be used by producers for crop nutrient management. Producers may also use the metric to gauge the effect of specific soil or crop management practices on the quality of their soils. For example, nematode genera that are sensitive to disturbance can be used as indicators for assessing the severity of soil physical disturbance or crop management practices (Zhao and Neher 2013). To this end, NCP has been used by several authors to describe the impact of different forms of disturbance on the nematode community in the vegetable production context (Bulluck et al. 2002a, Ruan et al. 2013, Li et al. 2014b, Reeves et al. 2014).

Although crop producers are under increasing pressure to improve the sustainability of their operations, economic considerations dominate the overall sustainability of modern-day crop production enterprises. For this reason, crop producers will always be interested in correlations between soil biology metrics and crop yield. It remains a challenge to demonstrate consistent correlations between soil biology metrics and crop yield. Aspects of NCP have been correlated with the yield of various crops, including tomatoes (Ferris et al. 2004, DuPont et al. 2009, Wang et al. 2014).

Since 2003, the largest commercial tomato producer in South Africa implemented a 'nature-friendly' open field production system. This particular example of eco-agriculture has been described in literature, albeit superficially (Uphoff and Thies 2011). Managing the soil microbiological content and diversity by means of compost, manures, compost tea, and Effective Microorganisms® formed an important part of this tomato production system. The objectives of this study were to investigate at a scientific level the following: i) the impact of soil disturbance and crop management, i.e. the conversion of natural vegetation into tomato production units, on the soil nematode communities, and ii) whether there was a link between tomato crop productivity and NCP metrics.

6.2 Materials and methods

6.2.1 Tomato production region

A detailed description of the production region appears in Chapter 3 (section 3.2.1).

6.2.2 Tomato production system

A detailed description of the production system appears in Chapter 3 (section 3.2.2).

6.2.3 Sampling strategy

Soils in various stages of the tomato production cycle were surveyed from 2009 to 2013. Samples were collected once from the various tomato production sites within the same bioregion. Soils were sampled from three-hectare open field tomato production units because the producers recorded tomato yield data at that scale. Twenty composite soil samples were taken at 15 cm depth with an auger from the production units. Soil samples reached the laboratory within 24 hours. Samples were taken 10 weeks before planting when field clearing and ridging activities commenced (referred to as pre-plant soil) (56 samples, 45 %) and during the first ten weeks after planting (referred to as cultivated soil) (28 samples; 23%). Soil samples were also taken from undisturbed sites (referred to as natural soil) in the same bioregion (39 samples, 32 %), giving a total of 123 samples. The different groups of samples represented a soil management gradient which described a change in plant communities from natural grasslands, to bare soil and then to a homogenous population of a non-indigenous cultivated plant species, the tomato (Table 6.1).

TABLE 6.1: Description of sample sites according to disturbance levels and soil quality variables (mean ± standard error)

Site	**Description**	**N**	**pH**	**Stone (%)**	**Clay (%)**	**Silt (%)**	**Sand (%)**
Natural	Undisturbed soils covered by natural vegetation	39	5.51 ± 0.10	10.7 ± 2.5	9.9 ± 1.8	5.9 ± 0.5	84.2 ± 2.1
Pre-plant	Disturbed soils (freshly tilled, bare soil)	56	5.82 ± 0.08	10.5 ± 1.5	10.8 ± 0.8	6.0 ± 0.3	83.2 ± 1.0
Cultivated	Disturbed soils (synthetic and organic fertilization, synthetic pesticides, monoculture of non-indigenous plant)	28	6.12 ± 0.16	12.2 ± 2.5	5.6 ± 1.2	4.8 ± 0.6	89.6 ± 1.7

6.2.4 Analyses

Soil physical properties were analysed according to standard methods (The Non-affiliated Soil Analyses Work Committee 1990) by a commercial soil testing laboratory (Bemlab, Somerset-West, South Africa). Sand, silt, and clay content were determined with the hydrometer method on samples taken at 15 cm depth. Soil was air dried, sieved through a 2 mm sieve for determination of the stone fraction (weight/weight basis) and analysed for pH (1.0 M KCl).

Nematode community analyses were performed by a commercial nematode testing laboratory (Nemconsult, Upington, South Africa). Free-living nematodes (FLN) as well as PPNs were extracted according to the decanting sugar flotation procedure (Pofu and Mashela 2012) and counted/identified by means of microscopy. Nematodes were identified to genus level only. Nematodes were assigned to trophic groups according to Yeates et al. (1993). Free-living nematodes included all the non-plant-parasitic nematode trophic groups, whereas PPNs included mostly the ectoparasites and the free-living stages of endoparasites (i.e., *Meloidogyne* spp.). The genus *Tylenchus* is ubiquitous to the soil environment and was classified as a fungivore (McSorley and Frederick 1999). The nematode community composition data was used in subsequent NCP calculations according to the procedures reported in the literature (Bongers 1999, Ferris et al. 2001; Table 6.2).

TABLE 6.2: Summary of variables used for nematode community profiling

Variables[a]	Units
Total population	
	numbers 250 cm^{-3} (#) number of taxa 250 cm^{-3}
Trophic groups	
Bacterivores (BF); Free-living nematodes (FLN); Fungivores (FF); Herbivores; Omnivores; Plant-parasitic nematodes (PPN); Predators	numbers 250 cm^{-3} number of taxa 250 cm^{-3} % of population (% p)
Individual genera	
	numbers 250 cm^{-3} % of population % of trophic group (% tg)
Colonizer-persister (c-p) classification	
c-p 1; c-p 2; c-p 3; c-p 4; c-p 5	% of population
Indices or ratios	
Basal Index (BI); Channel Index (CI); Enrichment Index (EI); FF/(FF+BF) ratio; (FF+BF)/PPN ratio; Maturity index (MI): MI1-5, MI2-5; Plant-Parasitic Index (PPI); Shannon's diversity index (H); Structure Index (SI)	index or ratio

a. See Materials and Methods for a detailed discussion on the interpretation of the colonizer-persister classification and subsequent functional guild indicators

According to the seminal work of Ferris et al. (2001), soil nematodes are assigned to five ecological competency groups (colonizer-persister or c-p groups) according to their responses to nutrient enrichment and physical disturbance in their immediate habitat: c-p 1 (multiplies rapidly in response to nutrient enrichment, mostly bacterivores), c-p 2 (lower reproduction rate than c-p 1's, very tolerant of unfavourable conditions, mostly bacterivores and fungivores), c-p 3 (low reproduction rate, very sensitive to environmental disturbance, mostly plant-parasitic nematodes but some bacterivores and fungivores), c-p 4 (lower reproduction rate, greater sensitivity to environmental disturbance, mostly omnivores, carnivores and some PPNs), and c-p 5 (slowest reproduction rate, large body sizes, greatest sensitivity to environmental disturbance, mostly omnivores, carnivores and some PPNs). By applying these indicators to a nematode community dataset, the user can glean more insight into the biophysical condition or history of the soil. For example, an increase in the abundance of c-p 1 nematodes indicates excessive nutrient enrichment in the form of organic or synthetic fertilizer (typically low C:N ratio soils). An increase in c-p 4 and c-p 5 nematodes indicates the absence of tillage (physical disturbance) or low nutrient enrichment (typically high C:N ratio soils).

Functional guild analysis involves the calculation of additional indices from the c-p and trophic grouping data (see Ferris et al. 2001 for a complete treatise): the basal index (BI), enrichment index (EI), structure index (SI), channel index (CI), maturity index (MI) and the plant-parasitic index (PPI). The BI describes the basal condition of the nematode-based soil food web based on the dominance of the c-p 2 bacterivores and fungivores. The EI and SI focus on the nematode guilds that indicate nutrient enrichment (c-p 1 and 2 bacterivores and fungivores) and disturbance (the c-p 3-5 trophic groups) respectively. The CI is based on the ratio between bacterivores and fungivores; it is used to indicate whether organic decomposition pathways are dominated by bacteria (CI < 50) or fungi (CI > 50). The CI is calculated by means of the weighted contribution of c-p 1 bacterivores and c-p 2 fungivores only, whereas the direct calculation of the FF/(FF+BF) ratio is preferred by some nematologists. The MI is another weighted factor calculation based on the c-p classification of all the trophic groups (excluding PPNs). Small MI values are indicative of disturbance and large values indicate low disturbance of the soils. There is a debate about the inclusion of c-p 1 guilds in the MI calculation, which is why both versions of the calculation (MI 1-5 and MI 2-5) were included. The PPI is a maturity index based on only the c-p 3 to c-p 5 plant-parasitic nematodes. The PPI is calculated in order to indicate the dominance of PPNs in relation to other soil food web indicators (such as the MI). The PPI appear to be of direct relevance to crop growers, but its application may be limited because all PPNs are included in the calculation, thus under- or over-estimating the actual threat posed by specific nematode genera and species to susceptible or resistant crops.

6.2.5 Data analysis

Univariate statistics were performed with PAST (PAleontological STatistics version 2.07b; Hammer et al. 2001). Outliers were identified by the interquartile range method and substituted by winsorization. Data transformations were performed prior to data analysis: log10(x+1) (for nematode counts) and arcsin(√x) (for proportions). Statistical analyses were performed with transformed data, but actual data are used in tables. Levene’s test determined that data transformation did not improve the homogeneity of variances during preliminary ANOVA testing. Consequently, statistical significance was established with Welch’s F-test and *post hoc* means separation with pairwise Tukey's tests. Regression analysis was used to explore the associations between the nematode community variables and tomato yield. In all cases statistical significance was established at $\alpha = 0.05$. Error bars indicate the standard error of the means in all graphs.

6.3 Results

6.3.1 Soil management

The physical properties of the soils did not differ significantly ($P > 0.10$) between the natural and the prepared soils (Table 6.1). The soil pH did not differ significantly ($P > 0.10$) between the prepared and cultivated soils. The soil stone content was significantly ($P < 0.05$) higher and the clay content was lower in the cultivated soils (Table 6.1). The geology of the tomato production region was very variable and the dominant soil characteristics listed in Table 6.1 reflected this. According to the Harmonized World Soil Database (2012), the dominant soil type at a specific land coordinate often had a very low percentage of share relative to the other soil types in the same coordinate (for example, as low as 24% in some cases), which meant the parent material geology in a single square kilometre was often extremely variable. A similar level of variability existed for the actual soil physical textures of each plot.

Several of the community-scale functionality metrics changed significantly along the soil management gradient (Table 6.3). The proportion of free-living nematodes, c-p 1 nematodes, fungivores and the EI were highest in the cultivated soils due to the high level of disturbance. In contrast, the proportion of plant-parasitic nematodes, c-p 3, c-p 3-5 and the PPI were higher in the natural soils but were significantly lower in the cultivated soils. The MI and SI were similar between the various soil disturbance types ($P > 0.05$) despite the contribution of the c-p 3-5 nematodes to the calculation of the SI (data not shown; only significant differences are reported in the tables). The CI, an indication of whether organic matter decomposition pathways are dominated by bacteria or fungi, did not differ significantly between soil disturbance types (data not shown).

Specific nematode genera were sensitive to the soil disturbance gradient in the studied agroecosystem. The prevalence of *Helicotylenchus* spp., regardless of how the counts were presented, was significantly lower in the disturbed and cultivated soils than in the undisturbed soils (Table 6.3). The numbers and proportions of *Mesorhabditis* spp., *Paratrichodorus* spp. and *Pratylenchus* spp. were higher in the cultivated soils than the undisturbed soils. The numbers of *Rotylenchus* spp. was higher in the undisturbed soils than the cultivated soils. The proportion of *Cephalobus* spp. in the pre-plant soils was higher than in the undisturbed or cultivated soils.

TABLE 6.3: Change in nematode community functionality and genus abundance along a soil disturbance gradient

Variables[a]	Units	Soil disturbance			Welch's F test		Tukey's test[b]			
		Natural (N)	**Prepared (P)**	**Cultivated (C)**			**N vs P**	**N vs C**	**P vs C**	**HSD-value**
		Median			**F-value**	**P-value**	**P-value**			
c-p 1	% of total population	5.1	8.2	13.9	4.173	0.020	ns	0.004	ns	5.8
c-p 3		45.3	34.3	28.6	3.635	0.032	ns	0.006	ns	11.3
c-p 3-5		50.7	41.4	35.9	3.560	0.009	ns	0.009	ns	8.3
FLN		52.0	61.9	69.6	4.845	0.011	ns	0.001	ns	12.5
Fungivores		10.9	20.7	23.1	5.742	0.005	0.045	0.028	ns	7.4
PPN		47.9	38.1	30.4	4.845	0.011	ns	0.001	ns	12.5
EI	Index	36.1	47.1	52.5	4.556	0.014	ns	0.006	ns	13.9
PPI		1.449	1.150	0.925	4.749	0.012	ns	0.002	ns	0.281
Cephalobus spp.	% of total population	1.7	5.3	2.0	4.427	0.015	0.030	ns	ns	0.7
Helicotylenchus spp.		21.5	15.3	4.3	9.194	<0.001	ns	<0.001	0.018	3.3
Mesorhabditis spp.		0.8	2.1	6.0	6.657	0.002	ns	<0.001	0.009	0.6
Pratylenchus spp.		1.4	4.6	6.8	7.696	0.001	0.029	0.018	ns	0.8
Paratrichodorus spp.		0.1	0.5	1.5	4.484	0.015	ns	0.001	0.009	0.1
Cephalobus spp.	% of trophic group	4.7	14.9	5.6	4.715	0.012	0.028	ns	ns	2.3
Helicotylenchus spp.		38.0	35.7	8.4	12.650	<0.001	ns	0.001	0.002	8.7
Mesorhabditis spp.		2.0	5.4	11.5	7.085	0.002	ns	<0.001	0.035	1.3
Pratylenchus spp.		3.4	14.0	18.2	10.790	<0.001	0.010	0.005	ns	2.5
Paratrichodorus spp.		0.4	2.6	9.2	5.160	0.009	ns	0.001	0.007	1.0
Cephalobus spp.	numbers 250 cm^{-3}	29.9	1.6	1.4	5.217	0.008	0.001	0.001	ns	6.6
Helicotylenchus spp.		169.7	118.0	7.7	20.320	<0.001	ns	<0.001	0.004	1697.1
Mesorhabditis spp.		4.1	10.2	34.3	4.274	0.017	ns	0.039	ns	2.9
Paratrichodorus spp.		0.8	3.0	11.3	3.928	0.025	ns	0.002	0.015	0.8
Pratylenchus spp.		13.1	26.4	67.5	3.960	0.024	ns	0.024	ns	20.8
Rotylenchus spp.		97.1	38.9	26.6	2.751	0.071	ns	0.046	ns	150.2

[a] Only significant and meaningful differences ($\alpha = 0.05$) are reported; FLN = free-living nematodes; PPN = plant-parasitic nematodes; c-p = colonizer-persister group; PPI = plant-parasitic index; EI = enrichment index. [b] Tukey's test results of pairwise comparisons; HSD = honestly significant difference, based on back transformed means, ns = not significant ($P > 0.05$)

Information from the various indices can be represented visually as integrated graphs. The faunal profile confirmed the insignificant differences between the various forms of soil disturbance, but visualized the change in the EI along the soil disturbance gradient (Fig. 6.1B). This change was very subtle based on the average of the data, but variation was substantial between each sample (Fig. 6.1A). The enrichment profile combines the percentage of bacterivores, fungivores, and herbivores on a ternary plot (Fig. 6.2). This presentation of the data was able to distinguish between the different forms of soil disturbance, albeit only slightly. According to Fig. 6.2, the balance in the nematode population shifted from higher proportions of bacterivorous and herbivorous than fungivorus nematodes (in the natural soils) to a population containing more fungivorus but less herbivorous nematodes (in the cultivated soils).

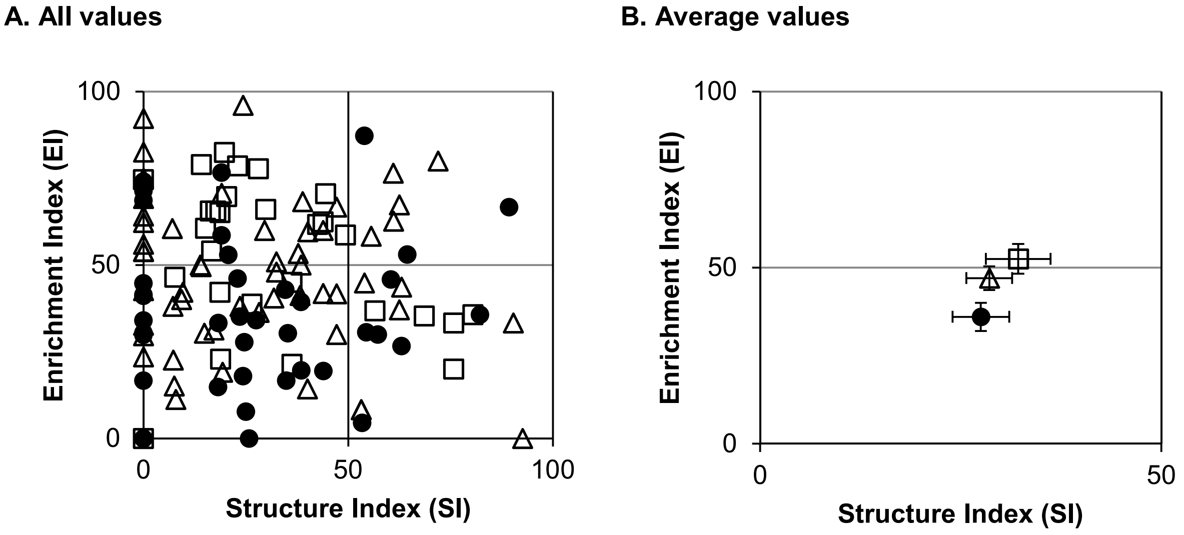
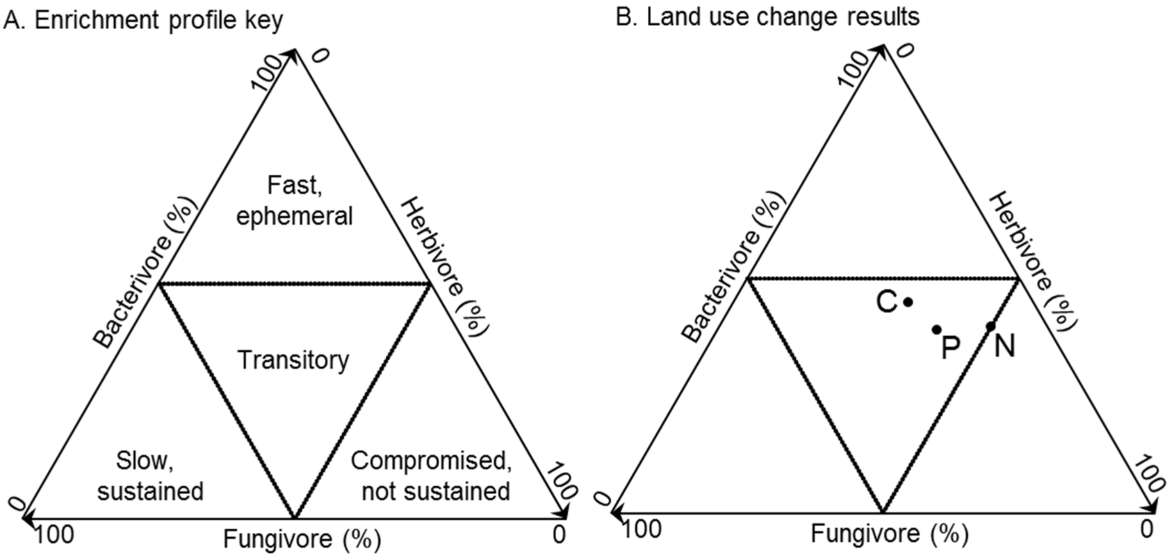


FIG. 6.1: Effect of soil disturbance on the nematode community enrichment and structure indices in natural (●), prepared (Δ), and cultivated (□) soils



Key: natural (N), pre-plant (P), and cultivated (C) soils

FIG. 6.2: Impact of soil disturbance on the nematode community enrichment profile (modified from Ferris and Bongers 2006)

6.3.2 Correlations with tomato yield

Correlation analysis was used to identify candidate variables for constructing a tomato yield prediction model. Regression models were constructed based on the data for samples taken before and during the crop cultivation stage.

For the pre-plant soil dataset, correlation analysis identified seven candidate variables for constructing a tomato yield prediction model: c-p 3-5 (%), bacterivores (%), *Cephalobus* spp. (% of total), *Diptherophora* spp. (% of total and tg), *Acrobeles* spp. (% of tg) and *Granonchulus* spp. (% of tg). However, the yield prediction regression model constructed using these variables was not satisfactory ($R^2 = 0.440$).

For the cultivated soil dataset, soil pH, *Paracrobeles* spp., the total number of taxa and the number of FLN taxa correlated positively with tomato yield (Table 6.4). Negative correlations with tomato yield were observed for three plant-parasitic nematodes genera (*Criconemella* spp., *Paratrichodorus* spp. and *Rotylenchus* spp.), a bacterivorous genus (*Panagrolaimus* spp.) and a fungivorus genus (*Aphelenchus* spp.). Indices associated with bacterivorous nematodes (i.e., the number of taxa and its proportion of the total population) correlated negatively with tomato yield.

TABLE 6.4: Correlations of nematode variables observed in cultivated soils with tomato yield[a]

Variable[b]	**r**	**R^2**	**P-value**
Aphelenchus spp. (% of tg)	-0.383	0.152	0.040
Aphelenchus spp. (%)	-0.395	0.178	0.025
Bacterivores (%)	-0.383	0.147	0.044
Bacterivores (no. of taxa)	-0.433	0.188	0.021
Criconemella spp. (% of tg)	-0.474	0.224	0.011
FLN (no. of taxa)	0.390	0.156	0.038
Panagrolaimus spp. (% of tg)	-0.426	0.181	0.024
Paracrobeles spp. (% of tg)	0.438	0.192	0.020
Paratrichodorus spp. (% of tg)	-0.459	0.211	0.014
pH	0.567	0.321	0.002
PPN (no. of taxa)	-0.479	0.229	0.010
Rotylenchus spp. (% of tg)	-0.474	0.224	0.011
Shannon's H	-0.542	0.293	0.003
Total no. of taxa	0.421	0.181	0.024
Zeldia spp. (% of tg)	-0.504	0.255	0.006

[a.] Only variables with a significant ($P \leq 0.05$) regression are shown. [b.] %: Proportion of the total nematode count; % of tg: proportion of the trophic group

Regression analysis was used to develop a predictive model based on the variables listed in Table 6.4 (Table 6.5; Fig. 6.3).

TABLE 6.5: Descriptive statistics of linear regression model for predicting tomato yield based on the nematode community profile of cultivated soils

Linear model components[a]	**Coefficient**	**Standard error**	**R^2**
Constant	46.697	49.724	-
Aphelenchus spp. (% of tg)	0.065	0.197	0.152
Aphelenchus spp. (%)	0.000	0.405	0.178
Bacterivores (%)	0.491	0.296	0.147
Bacterivores (no. of taxa)	-2.136	4.969	0.188
Criconemella spp. (% of tg)	0.968	0.745	0.018
FLN (no. of taxa)	3.576	11.926	0.156
Panagrolaimus spp. (% of tg)	0.161	0.406	0.181
Paracrobeles spp. (% of tg)	5.060	1.992	0.192
Paratrichodorus spp. (% of tg)	-0.827	0.343	0.211
pH	11.821	7.418	0.321
PPN (no. of taxa)	-4.430	12.665	0.229
Rotylenchus spp. (% of tg)	-0.536	0.239	0.224
Shannon's H	-33.184	13.273	0.293
Total no. of taxa	-0.252	10.369	0.181
Zeldia spp. (% of tg)	0.495	0.526	0.015

[a] %: proportion of the total nematode count; % of tg: proportion of the trophic group

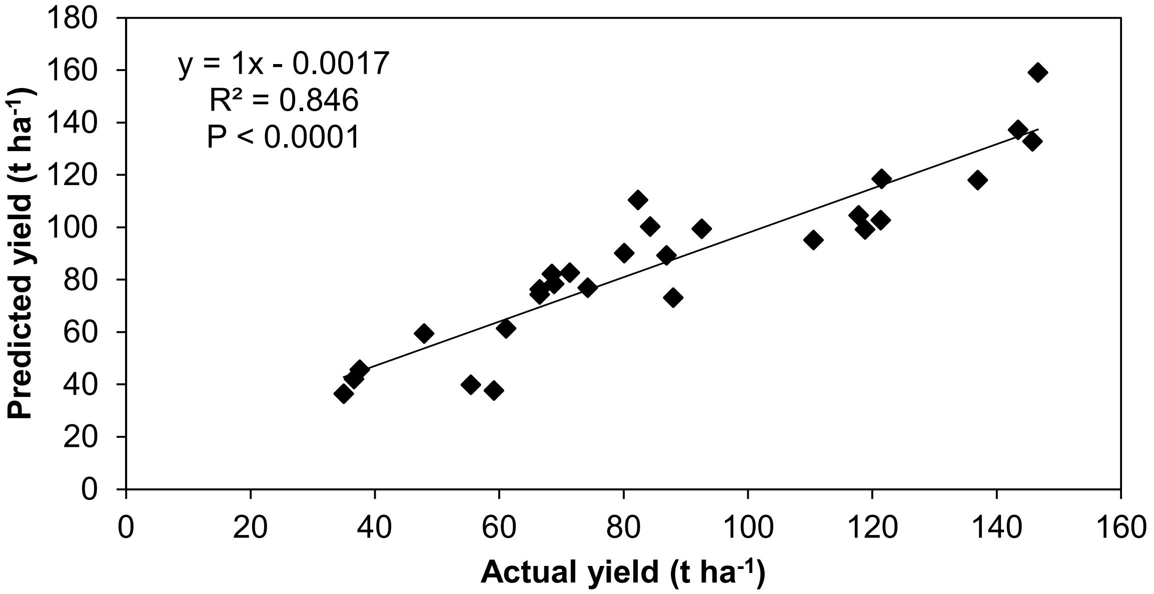


FIG. 6.3: Tomato yield prediction based on the nematode community profile of cultivated soils

Assessment of the FLN community in soil samples may not be available to crop producers as a routine analytical service because of additional costs or the local laboratory may not hold the required intellectual capital. For these reasons the conventional approach to yield prediction was followed by developing a regression model based on only the proportion of PPNs in the cultivated soils. The resultant linear regression model was not as comprehensive as the model outlined in Table 6.5 and Fig. 6.3, but the R^2 of 0.77 was satisfactory (Table 6.6; Fig. 6.4).

TABLE 6.6: Descriptive statistics of the linear regression model for predicting tomato yield based on the proportion of plant-parasitic nematodes in the cultivated soils

Linear model components	**Coefficient**	**Standard error**	**R^2**
Constant	122.9	12.6	-
Chitwoodius spp.	-322.5	312.6	0.083
Criconemella spp.	51.1	40.4	0.018
Ditylenchus spp.	17.3	35.1	0.003
Helicotylenchus spp.	-63.1	22.5	0.016
Longidorus spp.	352.5	227.8	0.0004
Meloidogyne spp.	23.3	25.3	0.129
Paratrichodorus spp.	-118.3	27.8	0.211
Pratylenchus spp.	-36.6	18.4	0.000
Rotylenchulus spp.	-85.9	59.9	0.022
Rotylenchus spp.	-93.4	22.1	0.224
Tylenchorhynchus spp.	-19.1	18.3	0.060
Xiphinema spp.	-491.9	401.5	0.005

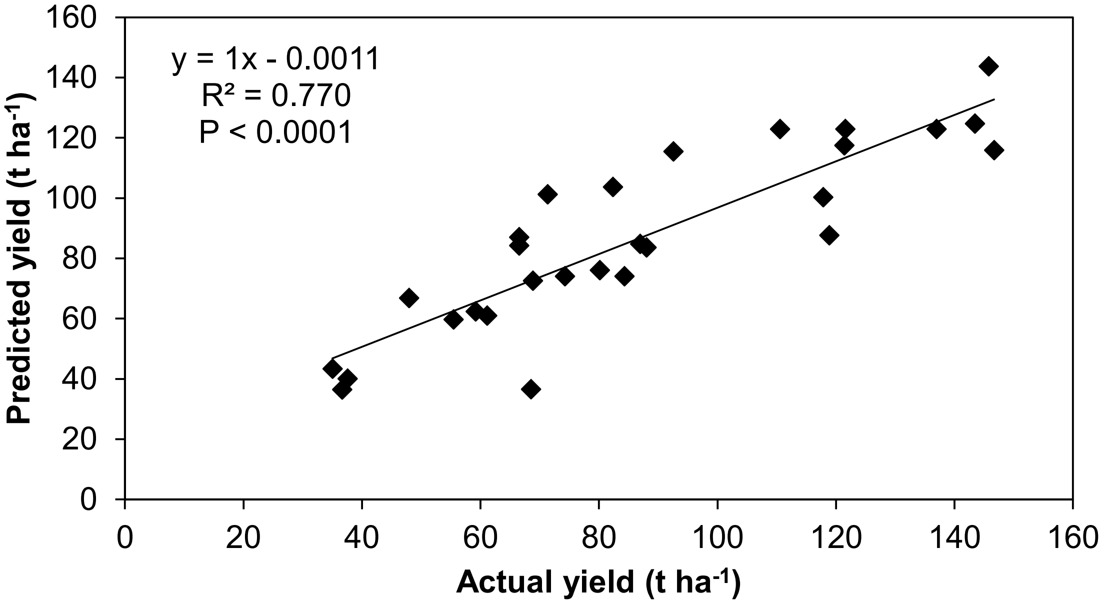


FIG. 6.4: Tomato yield prediction based on the plant-parasitic nematode community of the cultivated soils

6.4 Discussion

Successful commercial vegetable production relies on intensive tillage and heavy use of fertilizers and synthetic pesticides. Pressure is mounting on vegetable producers to improve the sustainability of their operations. Soil biology management is an important component of sustainable agriculture of the future and it has two facets: 1) beneficial soil biology contributes to nutrient cycling and disease suppression, while 2) plant-parasites continue to threaten crop productivity. Hence, there is a need for soil biology metrics with relevance to the economic and sustainability objectives of commercial vegetable production. In scientific literature, several soil health/quality metrics have been applied to the tomato production context (Tu et al., 2006). In this study we evaluated nematode community profiling as a means to study the effects of soil management on the soil food web as well as the association of NCP variables with tomato yield.

6.4.1 NCP and the soil disturbance gradient

Changes in functional guilds in response to soil disturbance were mirrored in several of the derived indices (EI, PPI, MI). The c-p 1 population - which was dominated by bacterivorous nematodes – was closely linked to the EI and increased 4.9-fold along the soil disturbance gradient. Bacterivores increase when organic matter in the form of compost is applied (Briar et al. 2011, Zhao and Neher 2013) or during intensive irrigation (Ferris et al. 2004). In our study, the EI ranged from moderate to high, but the SI was always low – this was in agreement with several studies on tomato or vegetable production systems (Bulluck et al. 2002a, Berkelmans et al. 2003, Ferris et al. 2004, Briar et al. 2011, Ugarte et al. 2013). The EI increases with soil disturbance (Liu et al. 2012) as soil microbes access organic matter exposed by tillage. Indeed, tillage reduced the SI and the particulate organic matter content of soils (Ugarte et al. 2013). The c-p 3 and c-p 3-5 populations - which was dominated by herbivores, omnivores, and predators – were closely linked to the SI calculation and declined along the soil disturbance gradient. The SI in our study was influenced by a decline in omnivores and predators and an increase in specific PPNs. The consistent use of tillage, synthetic fertilizers and pesticides probably contributed to the declining SI and increasing EI. Consequently, the SI was not a sensitive indicator of soil disturbance in the studied tomato production context, but similar findings were reported previously (Figure 1; Bulluck et al. 2002a, Briar et al. 2011). The faunal and enrichment profiles distinguished between soil disturbance changes and were sensitive to crop management effects associated with nutrient enrichment.

Specific nematode genera can be used as sentinels for describing the impact of soil and crop management. Our results indicated that *Mesorhabditis* spp. was a consistent indicator of nutrient enrichment and this was in agreement with previous studies (Zhao and Neher 2013). The resilience of *Cephalobus* spp. to tillage was confirmed in our study (Fiscus and Neher 2002) and *Helicotylenchus* spp. was identified as a candidate soil health indicator in the specific agroecosystem studied (to be discussed in more detail in section 6.4.4). The cost and complexity of analyses can be reduced by monitoring the occurrence of these genera in the soils of this tomato production region in South Africa.

The tomato producers in South Africa have also been exposed to the school of thought among academics and agri-consultants that place emphasis on measuring and managing the soil fungal and bacterial biomass ratios before and during crop production by means of compost and compost tea. Although the theory of this assertion was based on earlier ecosystem studies (Ingham et al. 1986, Griffiths et al. 1997, Dornbush et al. 2008), its relevance to sustainable vegetable production has not been demonstrated to date. The fungal:bacteria ratio is often reported in ecological studies, but apart from the peculiar limitations associated with each measurement technique (i.e., microscope-based assays vs molecular methods vs biochemical/metabolic procedures), the theoretical basis remains uncertain. Others used NCP as proxy for studying the soil food web at microbiological level, but results were inconclusive: the NCP indicators of fungal and bacterial dynamics were more reliable than actual measurements of fungal and bacterial biomass (Neher and Campbell 1994, Neher et al. 1999). From a functional index perspective, the CI aims to describe whether organic matter decomposition pathways were dominated by bacteria or fungi (Ferris et al. 2001). In our study, the CI did not differ between the soil disturbance types. Thus, the scientific relevance of the fungi:bacteria ratio in the agricultural context, not the natural ecosystems context, still requires clarification.

6.4.2 NCP and tomato yield

Tomato production is an intensive operation and agronomic success depends on rigorous tillage and heavy use of fertilizers and synthetic pesticides. PPNs remain a persistent risk to tomato growers all over the world. Intensification leads to increased PPN numbers but decreased PPN diversity in various cropping systems including tomatoes (Yardim and Edwards 1998, Ruan et al. 2013, Ugarte et al. 2013, Hu et al. 2014, Li et al. 2014b). Intensification leads to breakdown of nematode-related disease suppressive mechanisms (Sánchez-Moreno and Ferris 2007, McSorley et al. 2008, Carrascosa et al. 2014). Despite pursuing a 'nature-friendly' tomato production strategy, these South African producers consistently used high levels of synthetic pesticides, insecticides and herbicides in addition to the organic crop and soil management technologies. Furthermore, the use of *Meloidogyne* spp. resistant rootstocks might have favoured the selective amplification of PPNs not associated with crop failure in this tomato production region; similar observations were made by Johnson and Campbell (1980) and Greco and Di Vito (2011).

Regression analysis results highlighted the negative association of PPNs with tomato yield, even when the entire nematode community and associated indices were considered (Table 6.4). The combination of species of *Criconemella*, *Helicotylenchus*, *Meloidogyne*, *Paratrichodorus*, *Pratylenchus*, and *Rotylenchus* observed in the dataset is commonly observed in South African soils (Barbercheck and Von Broembsen 1986, Marais and Swart 2002). These nematodes are also described frequently in tomato production systems elsewhere in the world (Johnson and Campbell 1980, Cadet and Thioulouse 1998, McSorley et al. 1999, Bulluck et al. 2002a, Ferris et al. 2004, Briar et al. 2011, Anwar et al. 2013). Several of these genera are known to form galls or gall-like symptoms on tomato roots (i.e., 'stubby root' caused by *Paratrichodorus* spp.), an aspect that easily confound inexpert disease identification by producers and may lead to selection of cultivars with inappropriate disease resistance packages.

Crop health is influenced by the composition of PPN populations and the interactions between genera/species. The composition of the PPN community, the effect of the biophysical environment, and the presence of a plant host dictates the interactions of individual PPN genera relative to each other (Norton 1989). For example, root-knot and lesion nematodes are competitive and, thus, tend to be mutually exclusive in the same rhizosphere (Cadet et al. 2002, Chavez et al. 2014). *Helicotylenchus* spp. and *Pratylenchus* spp. competed with each other on *Pennicetum typhoides* and *Acacia holoserica* in West Africa (Villenave and Cadet 1998). On rice, *Tylenchorhynchus claytoni* suppressed *Helicotylenchus crenatus* (Prasad and Rao 1977). Hence, there exists an opportunity to manage the PPN balance and provide a form of biological control.

An unexpected result of our study was the negative correlations for the total number of taxa, the number of FLN taxa, omnivorous taxa and diversity as measured by the Shannon's diversity index, which suggests that high tomato yield is not associated directly with high nematode diversity, abundance of FLNs, or species richness (Table 6.4). This observation is in contrast to the general opinion that biodiversity of above- or below-ground biota and crop health are associated positively (e.g., Cardinale et al. 2003, McDonald 2014). Although Ferris et al. (2004) observed long-term positive and negative correlations between tomato yield and the EI and CI respectively, DuPont et al. (2009) observed highest tomato yields in bare fallow soils – the other land uses (cover crop mix, grain, and legumes) had 10-fold higher PPN numbers (as well as the characteristic high EI but low SI). It simply means that tomato producers will continue to pursue production in near-sterile soils, hence the continued use of solarisation, fumigation, and bare fallow as means of managing PPNs (Chellemi et al. 1993, 1997), regardless of the negative long-term implications for soil quality and agroecosystem health.

6.4.3 NCP in perspective

The presence/absence of plants was the primary distinguishing factor between nematode community profiles (NCPs) of different land uses (Gebremikael et al. 2014). In our study, the soil disturbance gradient described a change in plant populations from natural grasslands, to bare soil and then to a non-indigenous cultivated plant species, the tomato. Although this study highlighted the usefulness of community-level functionality metrics, its limitations were also observed. For example, biological nitrogen supply cannot be inferred from FLN numbers when a plant is present in the soil (Carrascosa et al. 2014, Gebremikael et al. 2014). Although there was evidence of enrichment, as visualized by the enrichment and the faunal profiles, the selective amplification of economically important PPNs was not detected by the community-level indices (also noted by Berkelmans et al. 2003). The decline in the PPI observed in our data (Table 6.3) would create the impression among tomato producers that their ‘nature-friendly’ production system was effective in reducing the PPN threat because herbivore numbers usually increase in tomato production systems over time (Bulluck et al. 2002a, Gebremikael et al. 2014). However, the increase in *Paratrichodorus* spp. and the concomitant decline of *Helicotylenchus* spp. during the soil management change could have important implications for the South African tomato producers (see section 6.4.5).

6.4.4 *Helicotylenchus* spp. as soil health indicator

Helicotylenchus spp. is commonly associated with the PPN community of tomato production systems and is endemic to soils in the traditional tomato producing regions in South Africa (Marais and Buckley 1993, Marais and Swart 2002). However, the economic impact of this nematode on tomato production is uncertain (Singh et al. 2013). Pure culture studies indicated that it caused tomato yield reduction at high densities, but had no effect at low densities (Tebenkova 1987). In other cropping systems, such as sugarcane and millet, *Helicotylenchus* spp. was identified as a mitigating species (Villenave and Cadet 1998, Cadet et al. 2002). In other words, when it was the dominating genus, *Helicotylenchus* spp. reduced the severity of infestations associated with *Meloidogyne* spp., *Pratylenchus* spp. and *Tylenchorhynchus* spp. Interactions of *Helicotylenchus* spp. and *Meloidogyne* spp. were observed for tomato production systems by other researchers (Tebenkova 1987). In our study, *Helicotylenchus* spp. appears to be a sensitive indicator of soil disturbance in the South African tomato production systems studied. Its positive influence on tomato yield could not be proven in this study. Other studies confirmed the sensitivity of *Helicotylenchus* spp. to tillage (Masse et al. 2002) and various forms of biotic, abiotic and xenobiotic stress (Liu et al. 2012). For this reason, *Helicotylenchus* spp. can be regarded as an indicator of soil health in this context, because its dominance is associated with undisturbed and 'natural' soils.

6.4.5 *Paratrichodorus* spp.: a 'new' threat to tomato producers?

Tomato producers are well-aware of the destructive capabilities of the more commonly studied PPNs such as *Meloidogyne* spp. and *Pratylenchus* spp. and their role in tomato disease complexes. Although the economic or agronomic impact of *Paratrichodorus* spp. infestations on tomatoes have been noted, it is not well described in literature or given only local importance (Anwar 1994, Greco and Di Vito 2011, Singh et al. 2013). It is often a component of PPN communities associated with tomatoes. The results of this study suggest that *Paratrichodorus* spp. was selectively amplified during soil disturbance change (Table 6.3) and was associated with yield reduction (Tables 6.4 and 6.5, Fig. 6.3 and Fig. 6.4). *Paratrichodorus* spp. are ectoparasites that feed on epidermal cells in the elongation and meristematic zone of the root (Schilt and Cohn 1975). These are known vectors of plant viruses (reviewed by Brown et al. 1989). Populations are higher in sandy and sandy loam soils in the presence of a suitable host (Schilt and Cohn 1975). Their numbers decrease in absence of a suitable host (Schneider and Ferris 1987), thus explaining the effectiveness of bare fallow and soil solarisation as control measure (Johnson and Campbell 1980, Chellemi et al. 1993, Chellemi et al. 1997, McSorley et al. 1999). However, control of *Paratrichodorus* spp. through solarisation and bare fallow was lost when duration was reduced or producers persisted with long-term monocropping of tomatoes (Johnson and Campbell 1980). Fumigation tends to increase their numbers (McSorley and McGovern 1996). Compost usage during a dry season increased *Paratrichodorus* spp.

numbers (McSorley et al. 1999). Additional treatment options include tactical flooding (McSorley et al. 1999) and rotations that include soybean (Chavez et al. 2014). Although the use of cover-crops may be deemed more ‘nature-friendly’ than more aggressive and interventionist approaches (i.e., the use of conventional or biological control measures), it may take a long time with uncertain outcomes (Masse et al. 2002, Lavelle et al. 2004, DuPont et al. 2009, Summers et al. 2014).

6.5 Conclusions

In this study we explored the utility of nematode community profiling (NCP) as soil biology management decision tool in a commercial open field tomato production system in South Africa. NCP was useful for describing soil disturbance in the South African tomato production region studied and the results were in agreement with other studies from other tomato production regions of the world. The numbers of individuals per genus, as well as their proportions of the total population and the trophic group were useful for exploring the correlation with tomato yield. However, it was unexpected to find negative correlations for the total number of taxa, the number of FLN taxa, omnivorous taxa, and diversity as measured by the Shannon diversity index, which means high tomato yield was not associated directly with high nematode diversity, abundance of FLNs, or species richness. Despite the useful information gleaned from these coarse-focus metrics, the importance of ecologically and economically important nematode genera was re-emphasized.

The findings of this study have application beyond the particular tomato production region of South Africa. At a practical level, the study highlighted the importance of basic plant pathology and its impact on crop yield. This is good news for growers who cannot access complex and expensive soil biology tests due to location or costs. Innovative growers risk suffering avoidable yield loss because of the unbalanced focus on a particular soil biology metric at the expense of common sense and sound agronomy. Having successfully dealt with nematode-related challenges a generation earlier, the next generation of tomato growers now need to consider the possibility that novel combinations of nematodes antagonists may pose a realistic threat to the viability of their enterprises. This study confirmed the undeniable value of biological science in the modern agricultural context. From the theoretical perspective, the study highlighted that soil health (and its testing) does not guarantee crop health when viewed from a soil food web functionality perspective only. Future research should focus on elucidating the interactions within the PPN community of this (and other) tomato production regions. Only then can plant-based control measures (i.e., rotations) be adjusted, in a scientific manner, in relation to the producers' specific soil biology management objective. This will go a long way to realize sustainable intensification and improve land care at the regional and national scales of focus.

Crop productivity is not only affected by plant-parasitic nematodes, but interactions with soil chemical and physical characteristics are also important. Since the late 1990's the concept of 'soil health' emerged. It is based on the integrated assessment of the soil's physical, chemical and biological characteristics and its impact on crop health. This approach is widely accepted by crop producers and the applied sciences researchers because it is an intuitive approach to assessing soil quality or soil health as opposed to the pure soil biology approach advocated by some (see Chapter 5). The limitations of the NCP metric were established in this study, which meant the usefulness of the integrated indicator assessment approach had to be evaluated (Chapter 7).

CHAPTER 7

APPLICATION OF INTEGRATED SOIL HEALTH TESTING IN SUPPORT OF SUSTAINABLE TOMATO PRODUCTION IN SOUTH AFRICA

Abstract

The economic situation in South Africa forces tomato producers to pursue intensive open field production systems. As a result, the soil resource is under increased pressure. The objective of this study was to find soil health or soil quality indicators suitable for on-farm testing in a resource-limited laboratory context in support of sustainable yet intensive tomato production. A range of biological, chemical and physical variables were tested for sensitivity to changes in soil management and the association with crop productivity. This study identified potentially mineralizable nitrogen, active carbon, soil aggregate stability, nematode community profiling, and available soil phosphorous (P) as robust soil health indicators. A different set of soil health indicators explained tomato yield variation in the multivariate context, most notably boron, soil aggregate stability (2-5 mm size fraction), *Paratrichodorus* spp., *Criconemella* spp. and the balance among the soil cations (especially exchangeable K). The association of the soil health indicators with tomato yield was also investigated. Multiple regression analysis was used to develop a tomato yield prediction model ($R^2 = 0.997$) based on a complex combination of soil biological, chemical and physical valuables (34 in total). Soil health testing remains a polyphasic, crop- and context-specific endeavour and must be reconciled to crop health. The association of low tomato yield with the presence of ectoparasitic nematodes (*Paratrichodorus* spp. and *Criconemella* spp.) in a soil of good physical and chemical quality challenges the simplicity and universality of the soil health concept. The identification of specific soil health variables that correlated with tomato productivity will benefit soil health policy development in support of sustainable vegetable production in the rural areas of Southern Africa.

Keywords: Active carbon, *Criconemella* spp., Exchangeable K, Multiple regression, Nematodes, *Paratrichodorus* spp., Potentially mineralizable nitrogen, Soil aggregate stability

7.1 Introduction

Long term soil quality/health decline is associated with the eventual decline of the stewards of the land and its soils (Scholes and Scholes 2013). Soil health means different things to different people. It must be recognized that soil quality is significantly and instantly altered during land-use change (Culman et al. 2010, Ouyang et al. 2013), but the time-scale for restoration of degraded soils is measured in decades (Dobson et al. 1997, Vasconcellos et al. 2013, Prest et al. 2014). Indeed, soil conservation is important given the very low slow soil formation rate of 0.1 mm year^{-1} (Stockman et al. 2014). The term *soil health* can be defined as 'the capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health' (Doran and Zeiss 2000). The terms *soil quality* and *soil health* are often used interchangeably (e.g., Karlen et al. 2003), however, *soil quality* refers to the intrinsic qualities of the soil that changes slowly over time (e.g., texture) whereas the term *soil health* refers to the dynamic qualities of the soil that changes quickly over time in response to agriculture (e.g., the biological component, soil structure). In the agriculture context, growers have specific requirements regarding soils (Table 7.1).

TABLE 7.1: Key soil requirements for sustainable crop production (from Gugino et al. 2009)

- Good soil tilth
- Sufficient depth
- Sufficient but not excess nutrients
- Small population of plant pathogens and insect pests
- Good soil drainage
- Large population of beneficial organisms
- Low weed pressure
- Free of crop limiting chemicals
- Resistant to degradation
- Resilient when unfavourable conditions occur

For the researcher, soil health is limited to the experimental tools available or the relevance of a specific research question. In the agricultural context for example, researchers associate soil health with nutrient cycling (Paul et al. 2014), the impact of tillage on soil quality (Mesa et al. 2014), or microbial biomass and activity (Monokrousos et al. 2006, Maul et al. 2014). From the crop producer's perspective, healthy soils do not cause plant diseases.

Currently there is no shortage of information about the importance of chemical and physical attributes to the effective functioning of soils and the resultant impact on crop productivity. The importance of the plant pathogenic aspect of the soil biological component is well-appreciated and remains an active research area for all crops. However, the potential role of the non-pathogenic side of the soil biology component remains largely misunderstood. Hence, greater emphasis will be placed on understanding the interactions between the various soil health components and more so the role of the soil biological component. The biological functionality of soils is a response to climate conditions, soil quality, and organic matter content, use of fertilizers and pesticides, and microbial nutritional requirements (Delcour et al. 2014, Hararuk et al. 2014, Nie et al. 2014, Nielsen et al. 2014).

Soil biology is susceptible to various stressors and disturbances which make these ideal candidates for soil health testing in support of sustainable agriculture (e.g., Monokrousos et al. 2006). However, the soil biological component is very complex and its analysis is costly, complex, variable, and often technically (and technologically) demanding. For this reason, several applied soil health/quality studies focussed only on soil chemical and physical attributes (Moebius et al. 2007, Li et al. 2013, Askari and Holden 2014). This is not an unreasonable approach because the activity and abundance of the soil biology component are governed to a large extent by the soil organic component and mineral physico-chemical factors (Feng et al. 2014, Gupta and Germida 2015). Although soils may be deemed healthy or of good quality from a pure physico-chemical perspective, the presence and activity of soilborne plant pathogens limits the utility of such indices or scoring systems, hence the integration of the concepts of 'soil health' and 'crop health' in recent studies (Janvier et al. 2007, Nayyar et al. 2009, Korthals et al. 2014, Mesa et al. 2014). Nematodes provide a solution to this dilemma because tillage affects the larger soil organisms more than the microbes (Kladivko 2001, Schloter et al. 2003). However, nematodes are not the only causes of crop disease, which necessitates the development of crop and context-specific soil health indicators.

The end-result of integrated soil health testing is often a scoring function or composite soil quality/health index (Idowu et al. 2009, Li et al. 2013, Ponge et al. 2013, Askari and Holden 2014, D'Hose et al. 2014, Swanepoel et al. 2014). Although such an approach may be beneficial for getting crop producers interested in soil health management, the relevance of interactions between soil health variables and possible interactions with crop health should be explored first (e.g., Li et al. 2013). In addition, the ideal indicator should be easy to analyze in resource-limited laboratories, cost-effective, robust to regional variation, and be able to absorb variation associated with inexpert sampling and handling of soils by unskilled personnel.

South African soils are particularly sensitive to deterioration because of the semi-arid climate and weathered soil parent material (Materechera 2014). In support of a large-scale commercial tomato production operation in the Limpopo Province of South Africa, the objective of this study was to find soil health or soil quality indicators suitable for on-farm testing in a resource-limited laboratory set-up. The study focussed on the following soil health indicators: soil chemistry, soil texture, aggregate stability and water holding capacity, active carbon, potentially mineralizable nitrogen (PMN), and nematode community profiling (NCP). To assist tomato producers with improving the sustainability of their operations, the indicators need to be sensitive to land-use change and crop productivity.

7.2 Materials and methods

7.2.1 Site description

The study concentrated on commercial open-field tomato operations in three bioregions of the Limpopo Province (Fig. 7.1, Table 7.2). The production regions differ in terms of climate, altitude and north-south/east-west orientation. The Central Bushveld bioregion supplies tomatoes from November to April; early or late frost and hail are the main yield-limiting factors. The mild winter climate of the Lowveld bioregion enables year-round tomato production; occasional cold spells in winter and high humidity during the summer production period limits yield in this production region. Very hot summers during November to January indicate why tomato production in the Limpopo River Valley bioregion occurs from February to May.

The tomato production system is described in Chapter 3 (see section 3.2.2).

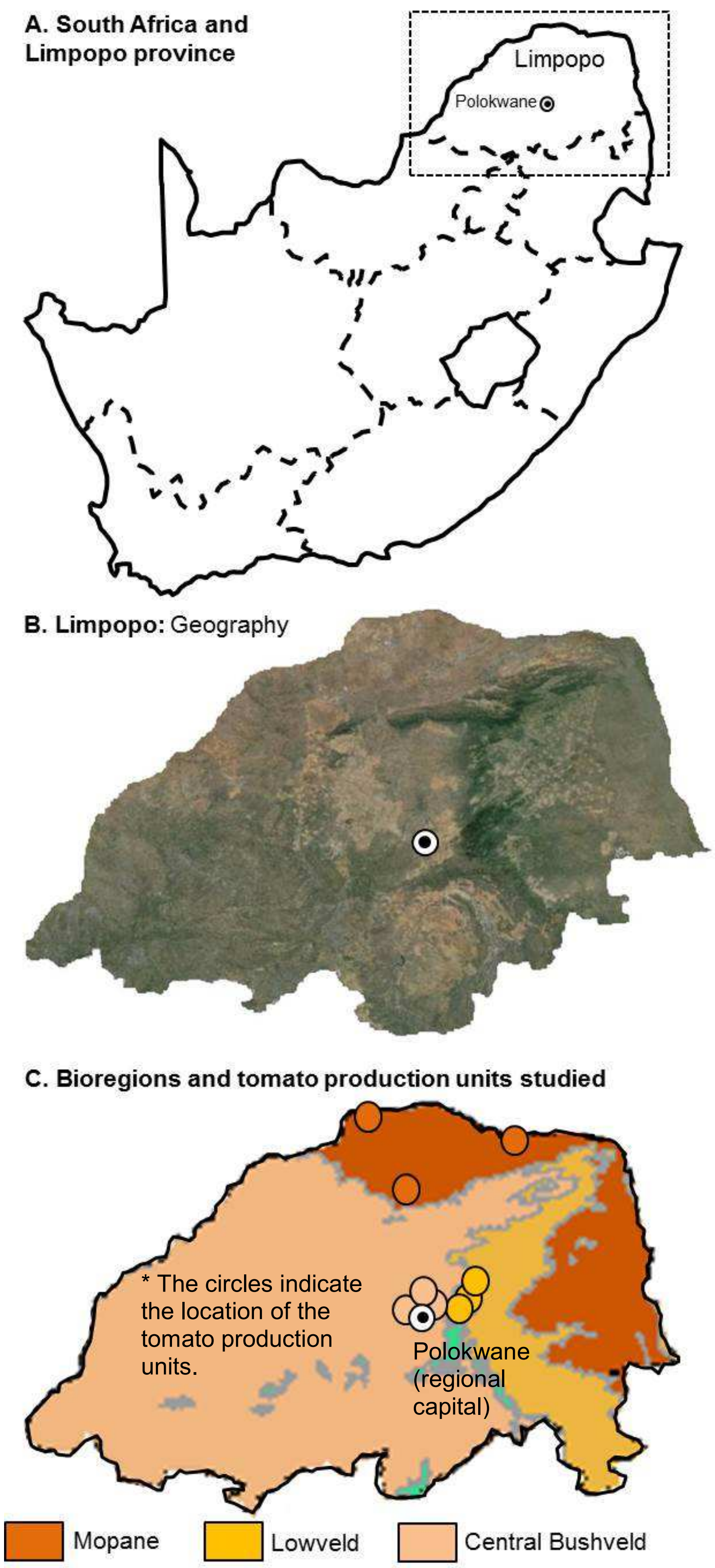


FIG. 7.1: Tomato production units surveyed in the Limpopo province.

TABLE 7.2: Main ecological, climatic, and geological characteristics of the three tomato growing areas subjected to soil biology testing from 2009-2012 (Mucina and Rutherford 2006)

Bioregion	Central Bushveld	Lowveld	Mopane
Vegetation types	Makhado Sweet Bushveld; Polokwane Plateau Bushveld	Tzaneen Sour Bushveld	Limpopo Ridge Bushveld; Musina Mopane Bushveld; Subtropical Alluvial Vegetation
Climate variables[a]			
Altitude (m)	1146-1233	631-832	388-744
MAFD (days)	7-11	1	1-4
MAP (mm)	454-500	781	311-419
MAPE (mm)	2122-2174	2097	2268-2303
MAT (°C)	16.9-18.5	19.7	20.9-21.7
Dominant soil types	Cambisol; Lixisol	Acrisol; Luvisol; Regosol	Cambisol; Regosol

[a] MAFD: mean annual frost days; MAP: mean annual precipitation; MAPE: mean annual potential evaporation; MAT: mean annual temperature

7.2.2 Sampling strategy

A survey of tomato production units was conducted from 2009 to 2012. Soil samples were collected randomly for soil biology testing by producers and agronomists. Soil samples were taken with an auger at 0-15 cm depth from three-hectare fields since the producers record their yield data at that scale. Samples were taken during the optimum growing season (referred to as ‘cultivated soil’) (40 samples; 23%). The remaining samples were taken when pre-plant field clearing and ridging activities commenced (referred to as ‘pre-plant soil’) (66 samples, 38 %). Paired samples were also taken from undisturbed sites (referred to as ‘natural soil’) in the same bioregions (69 samples, 39 %), giving a total of 175 samples. The samples from the pre-plant and cultivated soils were independent of each other (i.e., not linked to the same field). Samples reached the laboratory within 24 hours and were processed immediately.

7.2.3 Analyses

In order to follow an integrated approach to soil health testing, the chemical, physical and biological properties of the soil samples were determined.

Soil physical and chemical properties were analysed according to standard methods (The Non-affiliated Soil Analyses Work Committee 1990) by a commercial soil testing laboratory (Bemlab, Somerset-West, South Africa).

Sand, silt, and clay content were determined with the hydrometer method. Soil was air dried, sieved through a 2 mm sieve for determination of the stone fraction (weight/weight basis). Soil aggregate stability (SAS) was performed with the wet sieving technique of Haynes (1993). Water holding capacity (WHC) was determined at 10 kPa (field capacity) and 1500 kPa (permanent wilting point) using the pressure plate method of Peters (1965). The available moisture content (AMC) was calculated from the WHC results using bulk density values determined according to the wax method of Fox and Page-Hanify (1959). SAS, WHC and density measurements were done by the South African Sugar Research Institute (Mount Edgecombe, South Africa).

Soil pH was analysed in 1.0 M KCl. Soil P (Bray I) was extracted at pH = 2.6 with 0.025M HCl and 0.03M NH_4F. Soil P (BrayII) and total extractable cations, namely K, Ca, Mg and Na, were extracted at pH = 7 with 0.2 M ammonium acetate. Potassium, Ca, Mg and Na content results were reported as exchangeable (mg kg^{-1}), on a base saturation basis (%) and the T-value (the total exchangeable cation content). Soil carbon (C) content was determined by means of the Walkley-Black method. Micro-nutrients (Zn, Mn, Cu and Fe) were extracted with di-ammonium EDTA (0.02 M) and boron (B) using a 1:2 hot water ratio. The extracted solutions were analysed with a Varian ICP-OES optical emission spectrometer. Electrical conductivity (EC) was determined by measuring the resistance of saturated paste in an electrode cup. Extractable acidity was extracted with 1M KCl and determined through titration with 0.05 M NaOH.

Soil microbial activity was determined by two methods. Active carbon (AC) was determined by means of oxidation with 0.02M potassium permanganate according to the method of Weil et al. (2003). Potentially mineralizable nitrogen (PMN) was determined by means of the 7-day anaerobic incubation procedure of Drinkwater et al. (1996). Ammonium (NH_4^+) was extracted from soils at the start (T0) and after 7 days (T7) of the incubation using 2M KCl. The NH_4^+

was measured spectrophotometrically by means of the phenate procedure (Alleman et al. 1996). Nematode community analysis was performed by a commercial nematode testing laboratory (Nemconsult, Upington, South Africa) on 250 cm^3 soil samples. Free-living nematodes (FLN) as well as plant-parasitic nematodes (PPN) were extracted according to the decanting sugar flotation procedure (Pofu and Mashela 2012) and counted/identified by means of microscopy. Nematodes were identified to genus level only. Nematodes were assigned to trophic groups according to Yeates et al. (1993). Free-living nematodes included all the non-plant-parasitic nematode trophic groups, whereas PPNs included mostly the ectoparasites and the free-living stages of endoparasites (i.e., *Meloidogyne* spp.). The genus *Tylenchus* is ubiquitous to the soil environment and was classified as a fungivore (McSorley and Frederick 1999). The nematode community composition data was used in subsequent NCP calculations according to the procedures reported in the literature (Bongers 1999; Ferris et al. 2001; see Chapter 6 for methodology). Nematode results are reported as numbers 250 cm^{-3} soil (#), proportion of total population (% p), or proportion of the trophic group (% tg). The final dataset contained 231 variables (Table 7.3).

TABLE 7.3: Descriptive statistics of soil biological, chemical and physical variables related to three soil disturbance types (natural, pre-plant and cultivated) in three different tomato production regions (Central Bushveld, Lowveld and Mopane) in the Limpopo Province of South Africa. Values represent means (standard error). The key geography and climate characteristics of each production region appear in Fig. 7.1 and Table 7.2.

Production region		**Central Bushveld**			**Lowveld**			**Mopane**		
Soil disturbance		**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**
Number of samples		23	18	8	40	36	23	6	12	9
Variables[a]	**Units**[b]									
1. Field history										
Fallow duration	weeks	na	614.1 (104.8)	743.5 (130.2)	na	425.4 (38.2)	299.7 (31.9)	na	96.7 (24.4)	191.9 (101.8)
Times planted prior	number	na	2.8 (0.5)	2.3 (0.6)	na	3.6 (0.2)	3.1 (0.1)	na	3.8 (0.6)	3.7 (0.7)
2. Soil microbiology proxy-indicators										
Active carbon	mg kg^{-1}	535.9 (110.4)	753.6 (64.7)	308.7 (73.4)	616.9 (80.4)	766.2 (63.7)	102.8 (49.8)	137 (0.7)	484.3 (133.1)	204.2 (83.5)
Ammonium (time 0)	mg NH_4^+ kg^{-1}	2.5 (0.2)	1.7 (0.3)	3.4 (0.4)	2.6 (0.4)	3.8 (0.8)	2.6 (0.3)	2.5 (2.7)	3.6 (0.8)	2.6 (0.3)
Ammonium (time 7)	mg NH_4^+ kg^{-1}	7.2 (1.2)	3.0 (0.5)	6.0 (1.3)	9.9 (1.9)	4.4 (1.1)	4.5 (0.6)	8.1 (2.3)	5.3 (0.8)	5.2 (1.5)
PMN	μgN g^{-1} week^{-1}	4.5 (1.1)	1.3 (0.4)	2.6 (0.9)	7.3 (1.8)	0.6 (0.7)	1.5 (0.5)	5.7 (0.3)	1.7 (0.7)	2.6 (1.3)
3. Soil chemical characteristics										
B	mg kg^{-1}	0.3 (0.1)	0.3 (0.0)	0.3 (0.0)	0.4 (0)	0.3 (0)	0.2 (0)	0.4 (217.1)	0.6 (0.1)	0.4 (0.1)
C	%	0.7 (0.1)	0.6 (0.0)	0.6 (0.1)	1.1 (0.1)	0.6 (0)	0.5 (0)	0.3 (1.1)	0.5 (0)	0.4 (0.1)
Ca	mg kg^{-1} exch	716.1 (139.4)	702.6 (53.2)	795.5 (119.3)	1 325.2 (107.1)	1 474.4 (219.7)	909.8 (67.6)	1 820.0 (68.5)	2 222.2 (248.4)	1 472.0 (339.1)
Ca	% bs	47.5 (1.7)	56 (1.1)	54.0 (2.1)	60.4 (1.3)	61.3 (1.3)	59.1 (1.2)	66.2 (2.9)	62.0 (2.3)	66.2 (2.9)
Ca:Mg	ratio	1.7 (0.1)	2.4 (0.1)	2.1 (0.2)	2.7 (0.2)	2.8 (0.3)	2.8 (0.1)	3.6 (6.4)	2.3 (0.3)	3.2 (0.9)
(Ca+Mg)/K	ratio	8.2 (0.7)	8.1 (0.6)	9.2 (1.1)	16.5 (2.7)	17.2 (2.1)	7.9 (0.7)	19.5 (1.7)	12.0 (1.4)	7.7 (1.4)

[a] PMN: potentially mineralizable nitrogen; C: carbon (as measured by the Walkley-Black procedure)

[b] % bs: percentage base saturation basis; mg kg^{-1} exch: exchangeable cation basis

TABLE 7.3 (continued)

Production region		**Central Bushveld**			**Lowveld**			**Mopane**		
Soil disturbance		**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**
Variables[a]	**Units**[b]									
3. Soil chemical characteristics (continued)										
CEC	cmol+ kg^{-1}	5.6 (1)	5.3 (0.4)	3.5 (0.3)	8.3 (0.5)	8.5 (0.5)	5.4 (0.4)	6.0 (0.7)	10.6 (1)	6.3 (1.5)
Cu	mg kg^{-1}	4.0 (0.6)	7.1 (1.2)	5.7 (1.1)	6.1 (0.5)	9.8 (0.7)	7.7 (0.6)	2.4 (1)	5.4 (0.7)	4.2 (0.6)
Fe	mg kg^{-1}	134.7 (30.4)	246.3 (60.1)	293.2 (87.1)	163.5 (25.7)	185.3 (33.1)	195.4 (24.2)	276.4 (0.1)	68.6 (20.5)	179.5 (72.0)
K	mg kg^{-1} exch	256.7 (31.9)	259.8 (23.1)	272.5 (52.7)	289.4 (26.0)	261.2 (21.2)	314.6 (20.5)	269.3 (737.9)	427.1 (36.7)	333.3 (54.9)
K	% bs	10.7 (0.7)	10.6 (0.6)	9.4 (0.8)	7.7 (0.6)	7.1 (0.6)	11.9 (1)	7.6 (4.5)	6.8 (0.5)	8.6 (0.7)
Mg	mg kg^{-1} exch	274.5 (65.8)	178.5 (10.3)	238.7 (36.9)	308.9 (22.3)	309.6 (19.5)	202.8 (16.6)	281.3 (0.5)	547.6 (75.4)	329.2 (89.6)
Mg	% bs	29.2 (1.3)	24.2 (0.7)	26.5 (1.6)	24.2 (0.8)	25.1 (0.9)	22 (0.9)	21.4 (4.2)	25.5 (1.9)	23.2 (2.8)
Mg:K	ratio	3.1 (0.3)	2.5 (0.2)	3.1 (0.5)	4.7 (0.8)	4.8 (0.5)	2.2 (0.2)	4.5 (34.6)	3.7 (0.5)	2.0 (0.5)
Mn	mg kg^{1}	127.2 (13.5)	104.3 (10.1)	101.5 (21.3)	121.6 (8.3)	107.5 (10.0)	99.3 (6.7)	59.3 (0.2)	80.7 (16.2)	75.8 (19.5)
Na	mg kg^{-1} exch	67.3 (37.8)	50.6 (5.1)	117.9 (11.6)	40.8 (6.4)	56.0 (5.3)	34.1 (3.7)	33.7 (71.7)	219.6 (45.8)	52.8 (13.6)
Na	% bs	2.5 (0.5)	3.6 (0.3)	7.3 (0.5)	1.8 (0.3)	2.3 (0.2)	2.0 (0.2)	1.0 (2.2)	4.8 (0.7)	2.0 (0.3)
P (Bray I)	mg kg^{-1}	21.9 (5.6)	37.9 (7.2)	50.1 (16.4)	20.8 (2.2)	41.6 (3.2)	65.2 (5)	25.0 (25.3)	34.7 (4.3)	40.4 (8.8)
P (Bray II)	mg kg^{-1}	31.7 (7.7)	57.9 (12.0)	102.5 (42.9)	46.2 (7.8)	68.1 (5.8)	103.2 (10.1)	62.3 (71.9)	99.8 (30.7)	352.0 (179.0)
pH (KCl)	pH	5.3 (0.1)	5.6 (0.1)	6.2 (0.3)	5.4 (0.1)	5.6 (0.1)	5.8 (0.1)	6.2 (413.8)	6.9 (0.2)	7.0 (0.2)
Resistance	ohm	2 320.9 (331.1)	784.4 (83.5)	740.0 (63.9)	1 453.0 (137.5)	935.1 (78.4)	958.9 (81.7)	1781.7 (2.9)	555.4 (125.8)	1 472.2 (277.3)
Stone content	% vol	6.4 (1.4)	11.8 (2.6)	18.6 (4.7)	12.8 (2.6)	12.0 (1.7)	8.7 (1.9)	6.2 (7.7)	4.6 (1.4)	9.3 (4.2)
T-value	cmol kg^{-1}	7.3 (1.4)	6.2 (0.4)	7.4 (1.0)	10.6 (0.7)	11.2 (1.2)	7.5 (0.5)	12.5 (1.3)	17.8 (1.9)	11.2 (2.5)
Zn	mg kg^{1}	1.5 (0.2)	3.3 (0.6)	3.6 (1.1)	3.0 (0.4)	3.8 (0.3)	3.9 (0.3)	2.3 (14.3)	3.7 (0.3)	3.4 (0.3)

[a] CEC: cation exchange capacity; T-value: total exchangeable cation content

[b] % bs: percentage base saturation basis; mg kg^{-1} exch: exchangeable cation basis

TABLE 7.3 (continued)

Production region		**Central Bushveld**			**Lowveld**			**Mopane**		
Soil disturbance		**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**
Variables[a]	**Units**									
4. Soil physical characteristics										
AMC	mm m^{-1}	100.6 (3.3)	93.8 (1.2)	100.0 (4.2)	99.7 (2.1)	107.3 (1.5)	92.9 (2.0)	85.3 (54.3)	98 (4.7)	85.9 (6.6)
Clay (0-15 cm)	%	11.4 (2.6)	10.6 (1.1)	5.2 (1.4)	10.5 (1.2)	17.4 (1.3)	6.0 (0.8)	4.9 (0.9)	16.7 (2.2)	7.4 (3.3)
Density	g cm^{-3}	1.5 (0.0)	1.6 (0.0)	1.5 (0.0)	1.5 (0.0)	1.4 (0.0)	1.5 (0.0)	1.5 (5.6)	1.5 (0.0)	1.5 (0.0)
Sand (0-15 cm)	%	82.6 (3.1)	83.1 (1.4)	90.4 (1.3)	81.5 (1.7)	72.2 (1.8)	88.8 (1.2)	92.6 (2.0)	72.3 (3.8)	87.6 (5.0)
Silt (0-15 cm)	%	6.0 (0.7)	6.2 (0.6)	4.4 (0.6)	8.0 (0.8)	10.4 (0.8)	5.3 (0.4)	2.5 (2.2)	11.0 (1.7)	5.0 (1.7)
SAS (0.5-1 mm)	%	3.1 (0.8)	1.1 (0.4)	4.4 (1.4)	2.1 (0.3)	1.8 (0.3)	1.5 (0.2)	1.1 (2.4)	0.5 (0.1)	0.8 (0.2)
SAS (1-2 mm)	%	3.1 (1.0)	1.2 (0.3)	1.3 (0.2)	1.7 (0.2)	1.4 (0.2)	0.9 (0.1)	0.7 (0.4)	0.4 (0.1)	0.6 (0.1)
SAS (2-5 mm)	%	14.5 (2.5)	6.3 (1.0)	5.7 (1.4)	11.6 (1.2)	7.1 (0.6)	7.7 (0.8)	4.7 (0.3)	2.0 (0.9)	4.0 (1.2)
SAS (0.5-5 mm)	%	20.6 (3.6)	8.6 (1.1)	11.3 (1.3)	15.4 (1.3)	10.3 (0.8)	8.8 (0.8)	6.5 (0.9)	2.9 (1.0)	4.4 (0.9)
WHC (10 kPa)	% v/v	193.4 (17.9)	159.8 (6.2)	189.7 (20.2)	135.3 (17.8)	230.3 (12.2)	69.0 (14.7)	81.8 (15.5)	149.8 (31.3)	110 (43.7)
WHC (1500 kPa)	% v/v	96.8 (14.4)	66 (5.0)	89.7 (16.0)	73.2 (10.4)	128.7 (8.7)	34.8 (7.7)	33.2 (0.1)	81.0 (17.5)	61.7 (27.0)

[a] AMC: available moisture content; SAS: soil aggregate stability (mean weight diameter of aggregates); WHC: water-holding capacity

TABLE 7.3 (continued)

Production region	**Central Bushveld**			**Lowveld**			**Mopane**		
Soil disturbance	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**
Variables[a]									
5. Nematode community indicators									
5.1 Numbers (numbers of nematodes 250 cc^{-1} soil)									
Bacterivores	221.1 (45.5)	252.8 (81.4)	267.5 (57.6)	237.8 (32.2)	119.4 (26.9)	392.4 (115.8)	361.7 (1.0)	270.5 (88.6)	372.8 (135.1)
FLN	371.1 (60.3)	379.4 (108.7)	368.8 (58.8)	342.3 (47.5)	209.7 (39.6)	597.7 (145.1)	474.2 (97.5)	388.8 (106.0)	573.3 (154.9)
Fungivores	113.9 (26.3)	102.8 (27.7)	86.3 (34.1)	81.5 (20.5)	77.8 (20.4)	180.0 (39.6)	37.5 (0.2)	75.1 (21.6)	163.9 (58.7)
Omnivores	22.8 (6.2)	16.1 (4.1)	13.8 (6.8)	7.9 (2.4)	8.5 (2.6)	18.7 (3.5)	31.7 (0.3)	24.8 (11.6)	22.8 (10.2)
PPN	370.0 (60.5)	125.6 (29.7)	165.1 (76.8)	307.0 (47.6)	175.9 (34.9)	279.0 (58.8)	228.3 (7.9)	157.0 (38.3)	2 379.1 (1 862.2)
Predators	12.8 (5.7)	6.1 (2.5)	1.3 (1.3)	9.9 (2.8)	2.1 (1.2)	6.2 (1.7)	43.3 (0.3)	13.3 (7.6)	13.9 (5.6)
Total population	741.1 (95.9)	508.3 (114.1)	533.9 (81.7)	649.3 (82.5)	385.6 (62.2)	866.9 (158.2)	702.5 (1.7)	546.4 (131.0)	2 952.4 (1 944.3)
5.2 Taxa (number of taxa 250 cc^{-1} soil)									
Bacterivores	3.8 (0.4)	4.6 (0.4)	5.5 (0.8)	4.4 (0.3)	3.7 (0.4)	6.0 (0.7)	5.0 (12.4)	3.8 (0.6)	5.2 (1.1)
Fungivores	2.0 (0.2)	1.8 (0.2)	1.9 (0.4)	1.4 (0.2)	1.3 (0.2)	1.8 (0.2)	1.3 (31.6)	1.5 (0.3)	1.8 (0.3)
Omnivores	3.3 (0.3)	2.7 (0.3)	2.5 (0.3)	2.6 (0.2)	2.6 (0.2)	3.0 (0.2)	3.5 (0.0)	2.3 (0.3)	2.4 (0.4)
PPN	0.8 (0.1)	0.9 (0.2)	0.8 (0.2)	0.5 (0.1)	0.4 (0.1)	1.0 (0.1)	0.8 (4.4)	1.0 (0.1)	0.7 (0.2)
Predators	0.6 (0.2)	0.4 (0.1)	0.1 (0.1)	0.6 (0.1)	0.1 (0.1)	0.6 (0.1)	1.2 (25.8)	0.6 (0.2)	0.7 (0.2)
Total number of taxa	10.6 (0.7)	10.7 (0.8)	10.8 (1.1)	9.5 (0.6)	8.4 (0.8)	12.4 (1.0)	11.8 (11.1)	9.3 (1.2)	10.8 (1.5)

[a] FLN: free-living nematodes; PPN: plant-parasitic nematodes

TABLE 7.3 (continued)

Production region	**Central Bushveld**			**Lowveld**			**Mopane**		
Soil disturbance	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**
Variables[a]									
5.3 Proportions (% of total nematode population)									
Bacterivores	29.9 (4.5)	43.7 (5.0)	51.7 (7.7)	40.1 (3)	32.1 (4.4)	36.2 (3.8)	39.6 (4.7)	43.6 (5.5)	25.6 (4.4)
c-p 1	2.7 (1.3)	10.1 (4.3)	19.1 (5.3)	5.2 (1.2)	7.3 (1.4)	12.0 (2.5)	8.0 (9.4)	2.6 (1.0)	4.2 (2.5)
c-p 2	44.6 (3.9)	55.0 (5.6)	54.0 (6.5)	46.9 (3.0)	46.4 (4.5)	42.3 (3.5)	43.8 (12.9)	56.4 (6.1)	49.1 (10.5)
c-p 3	47.4 (5.0)	28.6 (4.7)	23.1 (9.1)	40.8 (3.4)	43.0 (4.6)	28.7 (5.0)	34.2 (1.5)	25.8 (6.1)	37.9 (11.3)
c-p 4	1.8 (0.6)	2.1 (0.5)	1.1 (0.7)	0.9 (0.3)	1.1 (0.5)	4.5 (1.4)	3.8 (4.6)	0.8 (0.6)	2.9 (1.7)
c-p 5	4.6 (1.3)	4.1 (1.0)	1.9 (1.0)	6.2 (2.1)	2.5 (0.7)	3.6 (1.4)	10.2 (9.2)	10.1 (5.2)	5.0 (2.5)
c-p 3-5	54.0 (4.7)	35.0 (4.8)	26.3 (8.8)	47.7 (3.4)	46.5 (4.8)	36.8 (5.5)	48.2 (8.2)	36.8 (6.2)	46.1 (11.4)
FLN	50.8 (4.6)	69.4 (4.8)	74.3 (8.7)	54.9 (3.4)	50.7 (4.8)	60.2 (4.4)	61.0 (11.1)	69.6 (5.6)	60.3 (11.2)
Fungivores	16.0 (2.6)	20.4 (4.0)	20.2 (7.0)	11.3 (1.6)	16.9 (3.1)	19.1 (3.0)	10.1 (4.8)	16.4 (5.1)	28.1 (9.7)
Omnivores	3.3 (1.1)	4.3 (1.0)	2.2 (0.9)	2.2 (0.7)	1.4 (0.4)	3.6 (1.2)	2.8 (2.2)	4.7 (1.1)	2.8 (1.6)
PPN	49.2 (4.6)	30.6 (4.8)	25.7 (8.7)	45.1 (3.4)	49.3 (4.8)	39.8 (4.4)	39.0 (32.8)	30.4 (5.6)	39.7 (11.2)
Predators	1.6 (0.6)	0.9 (0.4)	0.2 (0.2)	1.3 (0.3)	0.3 (0.1)	1.4 (0.6)	8.6 (1.0)	5.0 (3.7)	3.8 (2.3)
5.4 Indices									
Basal Index	69.1 (2.9)	63.9 (4.1)	57.5 (4.9)	67.3 (1.9)	59.7 (3.8)	59.1 (3.2)	58.3 (10.0)	65.8 (3.8)	61.1 (3.5)
Channel Index	66.9 (8.7)	64.2 (9.7)	26.8 (12.8)	46.9 (6.4)	44.4 (6.7)	37.0 (7.5)	63.5 (0.2)	52 (11.3)	60.4 (13)
Enrichment Index	34.4 (4.1)	42.3 (6.0)	58.5 (7.7)	31.5 (3.6)	45.4 (3.7)	53.0 (4.9)	35.5 (12.4)	30.1 (5.7)	44.6 (4.8)
MI1-5	2.4 (0.1)	2.1 (0.1)	1.9 (0.0)	2.1 (0.1)	1.8 (0.1)	2.2 (0.1)	2.3 (0.3)	2.3 (0.2)	2.3 (0.1)
MI2-5	2.4 (0.1)	2.0 (0.1)	1.6 (0.1)	2.0 (0.1)	1.7 (0.1)	2.0 (0.1)	2.2 (11.1)	2.3 (0.2)	2.2 (0.2)
PPI	2.9 (0.1)	2.9 (0.1)	2.2 (0.4)	3.2 (0.1)	2.9 (0.1)	3.0 (0.1)	3.0 (0.2)	3.0 (0.3)	2.1 (0.5)
PPI/MI	1.2 (0.1)	1.4 (0.1)	1.1 (0.2)	1.5 (0.0)	1.3 (0.1)	1.4 (0.1)	1.4 (0.3)	1.3 (0.1)	0.9 (0.2)
PPI/MI2-5	1.3 (0.1)	1.7 (0.3)	1.3 (0.2)	1.6 (0.1)	1.5 (0.1)	1.6 (0.1)	1.6 (0.2)	1.3 (0.1)	1.0 (0.2)
Shannon's H	1.7 (0.1)	1.9 (0.1)	1.7 (0.1)	1.7 (0.1)	1.6 (0.1)	2.0 (0.1)	2.0 (5.7)	1.8 (0.1)	1.4 (0.2)
Structure Index	35.1 (6)	34.0 (5.1)	21.1 (5.3)	23.9 (4.0)	14.7 (3.3)	34.8 (5.0)	47.3 (17.6)	37.2 (7.7)	38.4 (8.7)

[a]. c-p: colonizer-persister classification according to five ecological competency groups; MI: maturity index based on c-p 1-5 or c-p 2-5 data; PPI: plant-parasitic index; Shannon's H: diversity index

TABLE 7.3 (continued)

Production region	**Central Bushveld**			**Lowveld**			**Mopane**		
Soil disturbance	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**
Variables									
5.5 Nematode genera (numbers of nematodes 250 cc^{-1}soil)									
5.5.1 Bacterivores									
Acrobeles spp.	108.0 (31.3)	70.0 (24.6)	56.3 (21.9)	114.3 (19.7)	43.1 (11.3)	149.8 (40.7)	152.5 (13)	127.5 (44.1)	131.1 (54.5)
Acrobeloides spp.	5.7 (2.2)	22.8 (10.4)	8.8 (3.0)	15.5 (4.0)	5.8 (2.0)	28.3 (7)	22.5 (11.5)	11.3 (4.6)	39.4 (23.2)
Amphidelus spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.9 (0.9)	0.0 (6.7)	0 (0)	0 (0)
Cephalobus spp.	15.2 (8)	42.2 (17.0)	11.3 (5.8)	14 (3.6)	15 (4.7)	18.3 (6.3)	15 (23.3)	68.8 (30.5)	26.7 (15.9)
Chiloplacus spp.	5.2 (2.8)	3.3 (1.4)	1.3 (1.3)	9.8 (2.7)	2.8 (1.4)	7.8 (2.0)	36.7 (0.8)	9.6 (5.8)	25.6 (8.4)
Cruznema spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	10.9 (8.0)	0 (0)	0 (0)	0 (0)
Diploscapter spp.	0 (0)	0.6 (0.6)	2.5 (1.6)	0 (0)	0 (0)	0.9 (0.6)	0 (0)	0 (0)	0 (0)
Elaphonema spp.	37.8 (14.1)	0 (0)	1.3 (1.3)	27.3 (11.5)	1.7 (0.9)	1.7 (1.4)	0.8 (0.0)	1.7 (1.7)	0 (0)
Eucephalobus spp.	18.7 (10.8)	57.2 (47.9)	81.3 (51.0)	6.8 (2.6)	11.7 (3.5)	11.7 (3.5)	0 (0)	10.8 (4.2)	24.4 (14.8)
Mesorhabditis spp.	5.2 (2.9)	14.4 (8.9)	75.0 (22.0)	4.3 (3.0)	8.3 (3.0)	18.7 (4.8)	0.0 (1.7)	1.7 (1.1)	7.8 (5.7)
Monhystera spp.	0 (0)	0 (0)	0 (0)	0.5 (0.5)	0 (0)	0 (0)	0.0 (1.7)	0 (0)	0 (0)
Osstella spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1.7 (18.3)	0 (0)	0 (0)
Panagrolaimus spp.	4.3 (3.1)	0 (0)	1.3 (1.3)	5.3 (2.4)	8.3 (5.3)	99.6 (64.0)	18.3 (13.1)	6.7 (6.7)	8.9 (8.9)
Paracrobeles spp.	2.6 (1.3)	2.2 (1.0)	0 (0)	3.8 (1.7)	1.1 (0.5)	2.2 (1.8)	1.7 (64.5)	0 (0)	10 (4.7)
Plectus spp.	3.0 (1.5)	0.6 (0.6)	6.3 (5.0)	2.5 (1.6)	0.6 (0.4)	3.5 (1.8)	67.5 (0.0)	6.7 (6.7)	12.2 (8.8)
Prismatolaimus spp.	2.2 (1.8)	1.1 (0.8)	1.3 (1.3)	2.0 (1.1)	1.1 (0.5)	1.3 (1.0)	0 (0)	1.7 (1.7)	0 (0)
Rhabditida (uncertain) spp.	1.7 (1.7)	2.2 (1.3)	1.3 (1.3)	10.8 (5.1)	3.6 (1.8)	10 (3.9)	10.8 (0.0)	1.7 (1.7)	23.3 (11.4)
Rhabditis spp.	0.9 (0.6)	30 (22.2)	12.5 (7.3)	10.3 (4.7)	8.9 (2.6)	26.1 (10.4)	15.0 (9.9)	.0 (2.3)	36.7 (28.5)
Turbatrix spp.	0 (0)	0 (0)	0 (0)	0.3 (0.3)	0 (0)	0.4 (0.4)	0.0 (131.6)	0 (0)	0 (0)
Tylocephalus spp.	0 (0)	0 (0)	0 (0)	0.3 (0.3)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Wilsonema spp.	0.9 (0.6)	0.6 (0.6)	0 (0)	0.8 (0.4)	0.6 (0.6)	0 (0)	0.0 (18.2)	0 (0)	0 (0)
Zeldia spp.	7.0 (3.0)	5.6 (2.0)	7.5 (3.7)	9.5 (2.7)	6.9 (3.0)	16.5 (3.9)	19.2 (0)	12.1 (8.2)	30 (21.4)

TABLE 7.3 (continued)

Production region	**Central Bushveld**			**Lowveld**			**Mopane**		
Soil disturbance	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**
Variables									
5.5.2 Fungivores									
Aphelenchoides spp.	27.8 (19.5)	26.7 (12.6)	16.3 (9.4)	5.3 (2.5)	3.6 (2.4)	4.8 (2.1)	6.7 (8.9)	3.3 (1.4)	1.1 (1.1)
Aphelenchus spp.	26.7 (10.9)	33.9 (12.8)	6.3 (3.8)	43.8 (14.4)	32.2 (9)	29.1 (10.7)	30.0 (0.0)	35.4 (21.1)	111.1 (43.7)
Diptherophora spp.	0.9 (0.6)	0 (0)	0 (0)	0 (0)	0.8 (0.6)	0.4 (0.4)	0 (0)	0 (0)	0 (0)
Nothotylenchus spp.	2.2 (1.8)	0 (0)	0 (0)	0.3 (0.3)	0 (0)	0 (0)	0.0 (0.8)	0 (0)	0 (0)
Tylencholaimellus spp.	0.4 (0.4)	0 (0)	0 (0)	0 (0)	0.3 (0.3)	6.5 (6.5)	0 (0)	0 (0)	0 (0)
Tylencholaimus spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.0 (11.4)	0 (0)	2.2 (2.2)
Tylenchus spp.	54.1 (11.5)	45.6 (10.7)	63.8 (35.8)	30.8 (7.6)	42.5 (16.0)	125.2 (34.2)	0.8 (0.0)	35.8 (12.5)	37.2 (19.8)
5.5.3 Omnivores and Predators									
Aporcelaimellus spp.	16.5 (6.2)	10.6 (2.4)	12.5 (7.0)	4.8 (2.1)	7.5 (2.4)	12.2 (3.5)	18.3 (0.0)	20.8 (10.3)	10.0 (7.6)
Butleris spp.	0 (0)	0 (0)	0 (0)	0.3 (0.3)	0.6 (0.4)	0 (0)	0 (0)	0 (0)	0 (0)
Discolaimium spp.	0 (0)	0 (0)	0 (0)	1.3 (1.0	0 (0)	0.4 (0.4)	0.0 (20.7)	0 (0)	0 (0)
Discolaimoides spp.	5.2 (3.7)	0.6 (0.6)	0 (0)	2.5 (1.8)	0 (0)	0 (0)	29.2 (0.0)	0 (0)	1.1 (1.1)
Discolaimus spp.	0.4 (0.4)	0 (0)	0 (0)	0.3 (0.3)	0 (0)	0 (0)	0 (0)	2.5 (2.5)	5.6 (4.4)
Dorylaimida (uncertain) spp.	5.9 (2.4)	3.9 (2.3)	1.3 (1.3)	1.5 (0.6)	0.4 (0.3)	3.0 (0.8)	13.3 (0.0)	2.1 (1.7)	6.1 (5.0)
Dorylaimus spp.	0 (0)	0 (0)	0 (0)	0.3 (0.3)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Eudorylaimus spp.	0 (0)	0 (0)	0 (0)	1.3 (1.0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Granonchulus spp.	0 (0)	1.7 (1.2)	0 (0)	0.3 (0.3)	0.3 (0.3)	0 (0)	0 (0)	0 (0)	0 (0)
Koerneria spp.	0.4 (0.4)	0 (0)	0 (0)	0.3 (0.3)	0 (0)	0 (0)	0.0 (1.7)	0 (0)	0 (0)
Labronema spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1.3 (1.0)	1.7 (0.0)	2.1 (2.1)	0 (0)
Leptonchus spp.	1.7 (1.2)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	6.7 (6.7)
Mylonchulus spp.	0 (0)	0 (0)	0 (0)	1.3 (0.9)	1.1 (1.1)	1.3 (1.0)	0 (0)	5.8 (5.8)	0 (0)
Paraxonhium spp.	1.3 (1.0)	1.7 (1.7)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.4 (0.4)	0 (0)

TABLE 7.3 (continued)

Production region	**Central Bushveld**			**Lowveld**			**Mopane**		
Soil disturbance	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**
Variables									
5.5.3 Omnivores and Predators (continued)									
Prodorylaimus spp.	0 (0)	0 (0)	0 (0)	0 (0)	0.3 (0.3)	0 (0)	0 (0)	0 (0)	0 (0)
Pungentus spp.	0 (0)	0 (0)	0 (0)	0.3 (0.3)	0 (0)	1.3 (1.3)	0.0 (14.7)	0 (0)	0 (0)
Sectonema spp.	0 (0)	0 (0)	0 (0)	2.3 (1.2)	0 (0)	0 (0)	0.0 (1.7)	0 (0)	1.1 (1.1)
Tobrilus spp.	0 (0)	0 (0)	0 (0)	0.3 (0.3)	0 (0)	0 (0)	0.0 (11.5)	0 (0)	0 (0)
5.5.4 Plant-parasitic nematodes									
Boleodorus spp.	0.4 (0.4)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Chitwoodius spp.	0 (0)	2.2 (1.3)	0 (0)	0 (0)	0.6 (0.4)	0.4 (0.4)	20.8 (0.0)	0 (0)	0 (0)
Criconemella spp.	30.7 (21.6)	18.9 (8.3)	2.5 (2.5)	17.8 (6.3)	10.6 (3.6)	17.8 (3.3)	10 (43.3)	17.5 (10.5)	1.1 (1.1)
Ditylenchus spp.	3.5 (2.6)	0 (0)	6.3 (3.8)	2.0 (1.5)	16.7 (9.0)	1.7 (1.4)	10 (0.0)	0.8 (0.8)	5.6 (4.4)
Helicotylenchus spp.	141.3 (53.0)	51.7 (31.0)	8.8 (8.8)	128.8 (30.1)	97.2 (28.7)	56.3 (37)	43.3 (1.7)	27.5 (12.4)	0 (0)
Hemicycliophora spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1.7 (0.0)	0 (0)	0 (0)
Heterodera spp.	0.4 (0.4)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Longidorus spp.	0.9 (0.9)	0 (0)	0 (0)	0.5 (0.5)	0 (0)	0.4 (0.4)	5.0 (1.7)	0.8 (0.8)	2.2 (1.5)
Meloidogyne spp.	37.8 (32.5)	0.6 (0.6)	0 (0)	0.3 (0.3)	0 (0)	3.0 (3.0)	0.0 (9.8)	5.0 (5.0)	1816.1 (1815.5)
Paratrichodorus spp.	0.4 (0.4)	1.1 (1.1)	3.8 (1.8)	0.8 (0.6)	2.8 (1.6)	15.7 (6.3)	0.0 (5)	0 (0)	0.6 (0.6)
Paratylenchus spp.	6.1 (4.3)	2.2 (1.3)	0 (0)	0.8 (0.6)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Pratylenchus spp.	15.0 (5.5)	12.8 (3.3)	85.0 (68.3)	24.8 (9.1)	18.9 (3.4)	30.9 (7.2)	11.7 (0.0)	5.8 (3.4)	143.3 (86.9)
Rotylenchoides spp.	0 (0)	0 (0)	0 (0)	0 (0)	2.5 (2.5)	0 (0)	0.0 (6.8)	0 (0)	0 (0)
Rotylenchulus spp.	0 (0)	0 (0)	2.5 (2.5)	0 (0)	0 (0)	0 (0)	0.0 (25.9)	0 (0)	0 (0)
Rotylenchus spp.	103.5 (32.3)	30.6 (10.5)	2.5 (1.6)	88.5 (27.4)	18.1 (11.1)	32.4 (11.6)	42.5 (0.0)	13.3 (8.6)	13.3 (9.4)
Scutellonema spp.	14.8 (14.8)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.0 (46.4)	0 (0)	0 (0)
Tylenchorhynchus spp.	27.4 (12.1)	5.0 (3.2)	51.3 (44.5)	30 (14.1)	3.9 (1.8)	3.0 (2.2)	80 (0.0)	65.0 (30.5)	396.7 (240.7)

TABLE 7.3 (continued)

Production region	**Central Bushveld**			**Lowveld**			**Mopane**		
Soil disturbance	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**
Variables									
5.5.4 Plant-parasitic nematodes (continued)									
Tylenchulus spp.	1.3 (1.0)	0 (0)	0 (0)	3.5 (2.5)	0.3 (0.3)	0 (0)	0.0 (19.9)	0 (0)	0 (0)
Xiphinema spp.	5.7 (2.6)	0.6 (0.6)	0 (0)	6.8 (3.6)	0.3 (0.3)	0.4 (0.4)	1.7 (1.7)	0.4 (0.4)	0 (0)
Xiphinemella spp.	2.2 (1.3)	0 (0)	0 (0)	2.8 (2.1)	4.2 (1.7)	0 (0)	1.7 (0.0)	10.0 (10.0)	0 (0)
5.6 Nematode community: proportions (% of the total population)									
5.6.1 Bacterivores									
Acrobeles spp.	12.2 (2.4)	12.7 (2.1)	11.2 (4.0)	17 (2.2)	9.3 (1.7)	13.9 (1.7)	13.3 (1.2)	20 (4.3)	7.3 (1.9)
Acrobeloides spp.	1.3 (0.6)	3.5 (0.9)	1.5 (0.5)	2.1 (0.5)	2.2 (0.8)	3.2 (1.1)	3.4 (1.0)	1.9 (0.7)	3.0 (1.3)
Amphidelus spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.2 (0.2)	0.0 (0.2)	0 (0)	0 (0)
Cephalobus spp.	1.8 (0.8)	9.2 (2.8)	2.4 (1.2)	5.7 (1.5)	6.6 (1.8)	3.0 (1.0)	1.4 (1.4)	11.5 (3.2)	1.3 (0.6)
Chiloplacus spp.	0.5 (0.2)	0.5 (0.2)	0.2 (0.2)	1.2 (0.3)	0.7 (0.4)	0.9 (0.3)	5.6 (0.6)	1.6 (0.8)	4.4 (1.8)
Cruznema spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.8 (0.6)	0 (0)	0 (0)	0 (0)
Diploscapter spp.	0 (0)	0.1 (0.1)	0.5 (0.4)	0 (0)	0 (0)	0.1 (0.1)	0 (0)	0 (0)	0 (0)
Elaphonema spp.	3.9 (1.5)	0 (0)	0.3 (0.3)	3.0 (1.2)	0.2 (0.1)	0.1 (0.1)	0.6 (0.0)	0.1 (0.1)	0 (0)
Eucephalobus spp.	4.7 (2.8)	5.0 (2.5)	14.1 (6.9)	2.4 (1.0)	2.9 (1.1)	1.4 (0.5)	0 (0)	2.0 (0.9)	1.0 (0.6)
Mesorhabditis spp.	1.2 (0.7)	3.7 (2.1)	15.3 (4.4)	0.6 (0.4)	1.6 (0.4)	1.9 (0.5)	0.0 (0.2)	0.4 (0.3)	1.4 (1.3)
Monhystera spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.0 (1.8)	0 (0)	0 (0)
Osstella spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.2 (2.5)	0 (0)	0 (0)
Panagrolaimus spp.	1.2 (1.0)	0 (0)	0.2 (0.2)	1.2 (0.7)	1.1 (0.6)	5.6 (2.1)	2.5 (1.9)	0.4 (0.4)	0.3 (0.3)
Paracrobeles spp.	0.4 (0.3)	0.6 (0.3)	0 (0)	0.5 (0.2)	0.6 (0.3)	0.1 (0.1)	1.8 (2.3)	0 (0)	0.6 (0.3)
Plectus spp.	0.7 (0.5)	0.1 (0.1)	0.9 (0.6)	0.2 (0.1)	0.1 (0.1)	0.3 (0.1)	4.4 (0.0)	0.4 (0.4)	0.4 (0.3)
Prismatolaimus spp.	0.4 (0.4)	0.2 (0.2)	0.3 (0.3)	0.2 (0.1)	0.1 (0.1)	0.2 (0.2)	0 (0)	0.1 (0.1)	0 (0)
Rhabditida (uncertain) spp.	0.1 (0.1)	0.6 (0.3)	0.3 (0.3)	1.4 (0.7)	0.7 (0.4)	0.8 (0.2)	2.2 (0.0)	0.8 (0.8)	2.0 (1.3)
Rhabditis spp.	0.2 (0.2)	5.7 (3.7)	2.8 (1.6)	1.8 (0.9)	3.7 (1.2)	2.8 (1.0)	2.9 (1.5)	0.9 (0.4)	0.6 (0.3)

TABLE 7.3 (continued)

Production region	**Central Bushveld**			**Lowveld**			**Mopane**		
Soil disturbance	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**
Variables									
5.6.1 Bacterivores (continued)									
Turbatrix spp.	0 (0)	0 (0)	0 (0)	0.1 (0.1)	0 (0)	0.1 (0.1)	0.0 (4.2)	0 (0)	0 (0)
Tylocephalus spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Wilsonema spp.	0.1 (0.1)	0.1 (0.1)	0 (0)	0.1 (0.1)	0 (0)	0 (0)	0.0 (0.8)	0 (0)	0 (0)
Zeldia spp.	1.0 (0.4)	1.3 (0.5)	1.7 (0.7)	2.1 (0.6)	2.0 (0.8)	2.0 (0.7)	1.2 (0.0)	2.2 (1.0)	3.1 (2.2)
5.6.2 Fungivores									
Aphelenchoides spp.	2.3 (1.5)	5.2 (2.3)	4.9 (3.5)	1.3 (0.7)	0.4 (0.2)	0.4 (0.2)	0.2 (4.2)	2 (1.5)	0.3 (0.3)
Aphelenchus spp.	4.2 (1.4)	5.8 (2.2)	1.5 (0.9)	5.7 (1.2)	7.3 (1.7)	3.8 (1.0)	9.3 (0.0)	8 (5.3)	20.5 (8.9)
Diptherophora spp.	0.1 (0.1)	0 (0)	0 (0)	0 (0)	0.1 (0.1)	0.1 (0.1)	0 (0)	0 (0)	0 (0)
Nothotylenchus spp.	0.3 (0.3)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.0 (0.6)	0 (0)	0 (0)
Tylencholaimellus spp.	0.1 (0.1)	0 (0)	0 (0)	0 (0)	0 (0)	1.1 (1.1)	0 (0)	0 (0)	0 (0)
Tylencholaimus spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.0 (0.9)	0 (0)	0.1 (0.1)
Tylenchus spp.	8.8 (1.7)	10.1 (2.6)	13.8 (6.6)	4.2 (1.0)	9.3 (2.6)	12.6 (2.7)	0.6 (0.0)	6.2 (2.3)	6.7 (2.8)
5.6.3 Omnivores and predators									
Aporcelaimellus spp.	2.5 (1.2)	3.6 (0.9)	1.9 (0.9)	1.7 (0.7)	1.3 (0.4)	2.5 (1.3)	1.0 (0.0)	3.4 (1.1)	1.2 (0.9)
Butleris spp.	0 (0)	0 (0)	0 (0)	0.1 (0.1)	0.1 (0.1)	0 (0)	0 (0)	0 (0)	0 (0)
Discolaimium spp.	0 (0)	0 (0)	0 (0)	0.1 (0.1)	0 (0)	0.2 (0.2)	0.0 (5.0)	0 (0)	0 (0)
Discolaimoides spp.	0.5 (0.3)	0.1 (0.1)	0 (0)	0.3 (0.3)	0 (0)	0 (0)	6.8 (0.0)	0 (0)	2.2 (2.2)
Discolaimus spp.	0.1 (0.1)	0 (0)	0 (0)	0.1 (0.1)	0 (0)	0 (0)	0 (0)	0.4 (0.4)	1.3 (1.0)
Dorylaimida (uncertain) spp.	0.7 (0.3)	0.4 (0.2)	0.2 (0.2)	0.2 (0.1)	0 (0)	0.4 (0.2)	0.9 (0.0)	0.2 (0.1)	0.2 (0.1)
Dorylaimus spp.	0 (0)	0 (0)	0 (0)	0.1 (0.1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Eudorylaimus spp.	0 (0)	0 (0)	0 (0)	0.1 (0.1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Granonchulus spp.	0 (0)	0.5 (0.4)	0 (0)	0.1 (0.1)	0.1 (0.1)	0 (0)	0 (0)	0 (0)	0 (0)
Koerneria spp.	0.1 (0.1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.0 (0.9)	0 (0)	0 (0)

TABLE 7.3 (continued)

Production region	**Central Bushveld**			**Lowveld**			**Mopane**		
Soil disturbance	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**
Variables									
5.6.3 Omnivores and predators (continued)									
Labronema spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.7 (0.6)	0.9 (0.0)	3.8 (3.8)	0 (0)
Leptonchus spp.	0.1 (0.1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1.5 (1.5)
Mylonchulus spp.	0 (0)	0 (0)	0 (0)	0.1 (0.1)	0.1 (0.1)	0.1 (0.0)	0 (0)	0.4 (0.4)	0 (0)
Paraxonhium spp.	0.2 (0.1)	0.3 (0.3)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.8 (0.8)	0 (0)
Prodorylaimus spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Pungentus spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.1 (0.1)	0.0 (0.6)	0 (0)	0 (0)
Sectonema spp.	0 (0)	0 (0)	0 (0)	0.3 (0.1)	0 (0)	0 (0)	0.0 (16.5)	0 (0)	0.1 (0.1)
Tobrilus spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.0 (0.6)	0 (0)	0 (0)
5.6.3 Plant-parasites									
Boleodorus spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Chitwoodius spp.	0 (0)	0.8 (0.5)	0 (0)	0 (0)	0.4 (0.4)	0.1 (0.1)	1.3 (0.0)	0 (0)	0 (0)
Criconemella spp.	1.8 (0.5)	6.3 (2.3)	0.9 (0.9)	2.7 (0.9)	4.9 (1.4)	6.1 (2.0)	1.2 (12.4)	1.5 (0.7)	2.2 (2.2)
Ditylenchus spp.	0.6 (0.6)	0 (0)	1.4 (1.0)	0.2 (0.1)	3.9 (1.8)	0.5 (0.5)	2.1 (0.0)	0.2 (0.2)	0.3 (0.2)
Helicotylenchus spp.	17.6 (5.7)	6.4 (3.3)	3.0 (3.0)	19.6 (3.5)	21.7 (4.1)	9.8 (4.3)	12.4 (0.9)	7.3 (4.5)	0 (0)
Hemicycliophora spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.9 (0.0)	0 (0)	0 (0)
Heterodera spp.	0.1 (0.1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Longidorus spp.	0.1 (0.1)	0 (0)	0 (0)	0.1 (0.1)	0 (0)	0.1 (0.1)	0.2 (1.1)	0.3 (0.3)	0.3 (0.3)
Meloidogyne spp.	4.1 (2.5)	0.1 (0.1)	0 (0)	0 (0)	0 (0)	0.1 (0.1)	0.0 (5.2)	1.1 (1.1)	11.1 (9.9)
Paratrichodorus spp.	0.1 (0.1)	0.2 (0.2)	0.7 (0.3)	0.1 (0.1)	0.4 (0.2)	1.7 (0.7)	0.0 (0.2)	0 (0)	1.1 (1.1)
Paratylenchus spp.	1.7 (1.2)	0.6 (0.3)	0 (0)	0.4 (0.4)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Pratylenchus spp.	1.5 (0.5)	3.4 (1.0)	10.7 (7.4)	4.3 (1.8)	11 (3.5)	6.7 (2.4)	6.4 (0)	0.8 (0.3)	5.1 (3.0)
Rotylenchoides spp.	0 (0)	0 (0)	0 (0)	0 (0)	0.3 (0.3)	0 (0)	0.0 (0.9)	0 (0)	0 (0)
Rotylenchulus spp.	0 (0)	0 (0)	0.6 (0.6)	0 (0)	0 (0)	0 (0)	0.0 (1.9)	0 (0)	0 (0)
Rotylenchus spp.	14.5 (3.8)	11.2 (4.0)	0.5 (0.3)	10.3 (3.1)	3.1 (1.5)	5.5 (2.0)	4.9 (0.0)	2.3 (1.4)	0.4 (0.3)

TABLE 7.3 (continued)

Production region	**Central Bushveld**			**Lowveld**			**Mopane**		
Soil disturbance	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**
Variables									
5.6.3 Plant-parasites (continued)									
Scutellonema spp.	1.1 (1.1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.0 (4.2)	0 (0)	0 (0)
Tylenchorhynchus spp.	4.1 (2.0)	0.8 (0.6)	7.2 (6.5)	3.1 (1.0)	1.8 (1.0)	0.3 (0.3)	8.3 (0.0)	12.7 (5.4)	19.1 (9.2)
Tylenchulus spp.	0.8 (0.6)	0 (0)	0 (0)	0.5 (0.4)	0.3 (0.3)	0 (0)	0.0 (0.8)	0 (0)	0 (0)
Xiphinema spp.	0.9 (0.4)	0.1 (0.1)	0 (0)	2.9 (1.5)	0.1 (0.1)	0 (0)	1.1 (0.2)	0.8 (0.8)	0 (0)
Xiphinemella spp.	0.3 (0.1)	0 (0)	0 (0)	0.5 (0.3)	1.0 (0.6)	0 (0)	0.2 (0.0)	0.6 (0.6)	0 (0)
5.7 Nematode community: proportion of the trophic groups (% of trophic group)									
5.7.1 Bacterivores									
Acrobeles spp.	41.7 (6.3)	33.0 (4.6)	26.5 (9.2)	41.3 (3.9)	28.7 (4.6)	42.1 (5.8)	38.5 (2.6)	41.7 (6.0)	28.0 (6.2)
Acrobeloides spp.	3.5 (1.8)	8.7 (2.4)	4.0 (1.9)	7.2 (2.0)	4.5 (1.4)	7.1 (1.9)	7.1 (8.2)	6.9 (3.6)	11.0 (4.1)
Amphidelus spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.4 (0.4)	0.0 (8.3)	0 (0)	0 (0)
Cephalobus spp.	5.0 (2.0)	20.0 (4.8)	5.4 (2.7)	14.2 (4.0)	12.4 (2.8)	11.6 (5.1)	9.1 (3.3)	25.9 (7.1)	5.5 (2.5)
Chiloplacus spp.	3.7 (2.3)	1.1 (0.5)	0.5 (0.5)	3.6 (1.0)	1.9 (1.0)	3.8 (1.6)	13.0 (1.3)	4.4 (2.3)	23.0 (9.6)
Cruznema spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1.8 (1.2)	0 (0)	0 (0)	0 (0)
Diploscapter spp.	0 (0)	0.1 (0.1)	1.0 (0.6)	0 (0)	0 (0)	0.3 (0.2)	0 (0)	0 (0)	0 (0)
Elaphonema spp.	10.3 (3.6)	0 (0)	0.4 (0.4)	6.3 (2.0)	1.1 (0.6)	0.3 (0.2)	1.3 (0.0)	0.2 (0.2)	0 (0)
Eucephalobus spp.	10.9 (4.5)	11.0 (4.4)	21.8 (8.3)	5.6 (2.5)	10.3 (3.3)	4.0 (1.6)	0 (0)	3.6 (1.6)	3.6 (1.9)
Mesorhabditis spp.	2.7 (1.6)	7.1 (4.0)	26.2 (6.3)	1.2 (0.7)	4.8 (1.2)	5.2 (1.6)	0.0 (0.5)	0.9 (0.6)	2.9 (2.6)
Monhystera spp.	0 (0)	0 (0)	0 (0)	0.1 (0.1)	0 (0)	0 (0)	0.0 (3.7)	0 (0)	0 (0)
Osstella spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.5 (5.1)	0 (0)	0 (0)
Panagrolaimus spp.	2.7 (1.9)	0 (0)	1.0 (1.0)	2.3 (1.3)	3.7 (2.3)	12.2 (3.3)	5.1 (4.1)	0.9 (0.9)	1.1 (1.1)
Paracrobeles spp.	2.6 (1.4)	1.7 (0.8)	0 (0)	1.4 (0.6)	1.3 (0.7)	0.2 (0.1)	3.7 (4.2)	0 (0)	2.6 (1.2)
Plectus spp.	3.2 (2.9)	0.9 (0.9)	2.2 (1.7)	0.6 (0.3)	0.2 (0.1)	0.6 (0.2)	8.5 (0.0)	0.9 (0.9)	2.0 (1.1)
Prismatolaimus spp.	1.0 (0.7)	1.1 (0.9)	0.5 (0.5)	0.6 (0.3)	1.7 (1.4)	0.3 (0.3)	0 (0)	0.2 (0.2)	0 (0)

TABLE 7.3 (continued)

Production region	**Central Bushveld**			**Lowveld**			**Mopane**		
Soil disturbance	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**
Variables									
5.7.1 Bacterivores (continued)									
Rhabditida (uncertain) spp.	0.2 (0.2)	1.8 (1.1)	0.5 (0.5)	3 (1.3)	1.5 (0.9)	1.6 (0.4)	4.6 (0.0)	2.8 (2.8)	5.2 (2.6)
Rhabditis spp.	2.4 (2.2)	9.1 (5.2)	5.3 (2.5)	4.9 (2.0)	7.7 (2.0)	7.2 (2.7)	6.3 (3.0)	1.8 (0.9)	4.9 (3.2)
Turbatrix spp.	0 (0)	0 (0)	0 (0)	0.2 (0.2)	0 (0)	0.2 (0.2)	0.0 (10.9)	0 (0)	0 (0)
Tylocephalus spp.	0 (0)	0 (0)	0 (0)	0.2 (0.2)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Wilsonema spp.	1.2 (1.1)	0.2 (0.2)	0 (0)	0.4 (0.2)	0.1 (0.1)	0 (0)	0.0 (1.5)	0 (0)	0 (0)
Zeldia spp.	4.0 (1.7)	4.3 (1.8)	4.9 (2.8)	6.3 (1.8)	3.5 (1.2)	5.7 (1.9)	2.4 (0.0)	6.7 (4.1)	10.6 (7.4)
5.7.2 Fungivores									
Aphelenchoides spp.	10.2 (5.1)	16.7 (5.7)	22.3 (10.2)	7.3 (3.3)	2.6 (1.9)	2.4 (1.0)	8.3 (8.2)	11.4 (8.2)	1.1 (1.1)
Aphelenchus spp.	22.5 (6.1)	33.5 (9.1)	8.9 (4.8)	41.1 (6.3)	33.6 (6.4)	19.8 (5.2)	90.0 (0.0)	25.5 (9.3)	60.7 (14.1)
Nothotylenchus spp.	3.3 (2.4)	0 (0)	0 (0)	0.1 (0.1)	0 (0)	0 (0)	0.0 (1.7)	0 (0)	0 (0)
Tylenchus spp.	49.6 (7.2)	44.2 (9.0)	56.3 (12.5)	33.4 (6.0)	42.6 (6.9)	51.8 (7.5)	1.7 (0.0)	45.9 (11.9)	26.2 (12.0)
Diptherophora spp.	0.4 (0.3)	0 (0)	0 (0)	0 (0)	0.4 (0.3)	0.5 (0.5)	0 (0)	0 (0)	0 (0)
Tylencholaimellus spp.	0.5 (0.5)	0 (0)	0 (0)	0 (0)	0.1 (0.1)	2.6 (2.6)	0 (0)	0 (0)	0 (0)
Tylencholaimus spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0.0 (20.0)	0 (0)	0.8 (0.8)
5.7.3 Omnivores and predators									
Aporcelaimellus spp.	41.5 (10.2)	51.7 (10.9)	62.5 (18.3)	25.6 (6.8)	31.4 (7.6)	50.5 (9)	26.0 (0.0)	63.2 (13.0)	31.9 (16.0)
Butleris spp.	0 (0)	0 (0)	0 (0)	2.5 (2.5)	4.6 (3.3)	0 (0)	0 (0)	0 (0)	0 (0)
Discolaimium spp.	0 (0)	0 (0)	0 (0)	3.9 (2.8)	0 (0)	4.3 (4.3)	0.0 (20.0)	0 (0)	0 (0)
Discolaimoides spp.	7.2 (4.0)	2.8 (2.8)	0 (0)	4.8 (3.4)	0 (0)	0 (0)	60.8 (0.0)	0 (0)	11.1 (11.1)
Discolaimus spp.	4.3 (4.3)	0 (0)	0 (0)	2.5 (2.5)	0 (0)	0 (0)	0 (0)	8.3 (8.3)	22.2 (14.7)
Dorylaimida (uncertain) spp.	25.2 (8.6)	15.0 (6.9)	12.5 (12.5)	13.1 (5.3)	3.3 (2.8)	25.7 (7.9)	40.6 (0.0)	9.4 (8.3)	12.5 (11.0)
Dorylaimus spp.	0 (0)	0 (0)	0 (0)	1.3 (1.3)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)

TABLE 7.3 (continued)

Production region	**Central Bushveld**			**Lowveld**			**Mopane**		
Soil disturbance	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**
Variables									
5.7.3 Omnivores and predators (continued)									
Eudorylaimus spp.	0 (0)	0 (0)	0 (0)	5.0 (3.5)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Granonchulus spp.	0 (0)	7.8 (5.9)	0 (0)	2.5 (2.5)	2.8 (2.8)	0 (0)	0 (0)	0 (0)	0 (0)
Koerneria spp.	4.3 (4.3)	0 (0)	0 (0)	0.6 (0.6)	0 (0)	0 (0)	0.0 (11.1)	0 (0)	0 (0)
Labronema spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	8.7 (6.0)	11.1 (0.0)	8.3 (8.3)	0 (0)
Leptonchus spp.	2.9 (2.9)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	11.1 (11.1)
Mylonchulus spp.	0 (0)	0 (0)	0 (0)	2.3 (1.6)	2.8 (2.8)	6.8 (4.9)	0 (0)	6.5 (6.5)	0 (0)
Paraxonhium spp.	7.2 (5.1)	3.3 (3.3)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1.7 (1.7)	0 (0)
Prodorylaimus spp.	0 (0)	0 (0)	0 (0)	0 (0)	1.4 (1.4)	0 (0)	0 (0)	0 (0)	0 (0)
Pungentus spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	3.7 (3.7)	0.0 (17.4)	0 (0)	0 (0)
Sectonema spp.	0 (0)	0 (0)	0 (0)	10.3 (4.7)	0 (0)	0 (0)	0 (0)	0 (0)	11.1 (11.1)
Tobrilus spp.	0 (0)	0 (0)	0 (0)	0.6 (0.6)	0 (0)	0 (0)	0.0 (7.2)	0 (0)	0 (0)
5.7.4 Plant-parasites									
Boleodorus spp.	4.3 (4.3)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Chitwoodius spp.	0 (0)	2.0 (1.4)	0 (0)	0 (0)	0.5 (0.5)	0.3 (0.3)	5.9 (0.0)	0 (0)	0 (0)
Criconemella spp.	4.2 (1.4)	16.2 (5.2)	2.5 (2.5)	7.4 (2.5)	16.0 (5.2)	14.0 (3.8)	2.2 (14.9)	6.1 (3.4)	5.6 (5.6)
Ditylenchus spp.	3.9 (3.7)	0 (0)	14.1 (7.5)	0.5 (0.3)	7.7 (3.5)	1.7 (1.5)	17.9 (0.0)	1.0 (1.0)	3.9 (3.7)
Helicotylenchus spp.	27.9 (8.1)	21.9 (8.3)	8.8 (8.8)	42.8 (6.4)	41.9 (6.4)	18.5 (7.2)	14.9 (1.5)	16.2 (8.2)	0 (0)
Hemicycliophora spp.	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1.5 (0.0)	0 (0)	0 (0)
Heterodera spp.	0.1 (0.1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Longidorus spp.	0.2 (0.2)	0 (0)	0 (0)	0.1 (0.1)	0 (0)	0.4 (0.4)	0.8 (5.6)	1.7 (1.7)	0.9 (0.9)
Meloidogyne spp.	9.9 (4.7)	0.6 (0.6)	0 (0)	0 (0)	0 (0)	1.9 (1.9)	0.0 (9.7)	6.3 (6.3)	13.4 (10.6)
Paratrichodorus spp.	0.5 (0.5)	1.1 (1.1)	4.4 (2.7)	0.9 (0.8)	1.9 (1.2)	11.6 (4.8)	0.0 (0.8)	0 (0)	2.8 (2.8)
Paratylenchus spp.	4.7 (3.9)	2.9 (2.2)	0 (0)	0.7 (0.7)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)

TABLE 7.3 (continued)

Production region	**Central Bushveld**			**Lowveld**			**Mopane**		
Soil disturbance	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**	**Natural**	**Pre-plant**	**Cultivated**
Variables									
5.7.4 Plant-parasites (continued)									
Pratylenchus spp.	2.8 (0.8)	18.2 (4.5)	28.6 (13.5)	8.9 (3.4)	15.8 (3.9)	15.3 (4.7)	14.6 (0.0)	3.0 (1.4)	12.7 (9.3)
Rotylenchoides spp.	0 (0)	0 (0)	0 (0)	0 (0)	0.7 (0.7)	0 (0)	0 (1.4)	0 (0)	0 (0)
Rotylenchus spp.	30.7 (7.3)	29.8 (8.9)	8.0 (6.3)	20.6 (5.6)	6.7 (2.9)	19.6 (5.9)	14.1 (0)	6.6 (4)	0.7 (0.5)
Rotylenchulus spp.	0 (0)	0 (0)	5.0 (5)	0 (0)	0 (0)	0 (0)	0 (4.7)	0 (0)	0 (0)
Scutellonema spp.	3.7 (3.7)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (11.6)	0 (0)	0 (0)
Tylenchulus spp.	1.2 (0.9)	0 (0)	0 (0)	0.7 (0.5)	0.7 (0.7)	0 (0)	0 (3.7)	0 (0)	0 (0)
Tylenchorhynchus spp.	7.6 (3.3)	5.5 (3.4)	12.6 (11.4)	8.4 (3.3)	3.3 (1.6)	1.0 (0.6)	21.9 (0)	32.9 (10.9)	38.0 (14.7)
Xiphinema spp.	1.6 (0.7)	1.9 (1.9)	0 (0)	7.9 (3.5)	0.2 (0.2)	0.3 (0.3)	5.6 (0.6)	8.3 (8.3)	0 (0)
Xiphinemella spp.	1.1 (0.7)	0 (0)	0 (0)	1.0 (0.6)	1.7 (0.8)	0 (0)	0.6 (0.0)	2.8 (2.8)	0 (0)

7.2.4 Data analysis

Univariate statistics were performed with PAST (PAleontological STatistics version 2.07b; Hammer et al. 2001). Outliers were identified by the interquartile range method and substituted by winsorization. Data transformations were performed prior to data analysis: log10(x+1) (for nematode counts) and arcsin(√x) (for proportions). Statistical analyses were performed with transformed data, but actual data were used in tables and figures. In all cases statistical significance was established with $\alpha = 0.05$. Error bars indicate the standard error of the mean in all graphs.

The first objective of this study was to identify the variables that were most sensitive to soil disturbance yet insensitive to spatial variations at the regional scale. Statistical significance between different soil disturbance types was established with ANOVA and *post hoc* means separation with Tukey's honestly significant difference (HSD) test. Multivariate Analysis of Variance (MANOVA) was done on transformed data using PAST.

The second objective of this study was to identify the variables associated with tomato yield variation. This dataset contained two elements: data from soils sampled during the pre-plant stage and data from soils sampled during the first ten weeks of the tomato production stage. Data analysis was performed on each element separately. Principal Component Analysis (PCA) was performed with ADE-4 (Thioulouse et al. 1997). Regarding correlations of variables with principal components (PCs), the $r > |0.4|$ criterion was used to retain variables for interpretation. The retained variables were subjected to multiple regression analysis to develop a quantitative tomato yield prediction model (performed with PAST). Variables with a significant linear dependence were retained to refine the final model. Classification and regression tree (CART) analysis was done in R using *rpart* package (www.r-project.com). The robustness of the resulting tree was ensured by using the *cp* and *prune* functions.

7.3 Results

7.3.1 Soil management

To satisfy the objective of finding soil health indicators suitable for testing at resource-limited on-farm soil testing laboratories, the sensitivity of the variables to regional differences was determined. Two-way ANOVA was used to select variables that responded significantly to soil disturbance, but were insensitive to regional differences and soil disturbance/region interactions

(Table 7.4) – these were considered to be the primary indicators of soil health/quality for the Limpopo tomato production region.

TABLE 7.4: Primary soil quality indicators in the Limpopo tomato production region of South Africa

		Soil disturbance[b]			**ANOVA[c]**		
Variable[a]	**Unit**	**Natural**	**Pre-Plant**	**Cultivated**	**F-value**	**P-value**	**Tukey's LSD**
NH_4^+ (T7)	ppm	8.9a	4.2b	5.0b	8.0	<0.001	3.2
P (Bray I)		21.5c	39.3b	56.6a	29.1	<0.001	10.7
PMN	$\mu g\ g^{-1}$ week^{-1}	6.2a	1.0b	2.0b	12.9	<0.001	2.8
Bacterivores	numbers 250 cc^{-1} soil	242.9ab	183.3b	363.0a	4.5	0.013	143.2
Bacterivorous taxa		4.2b	4.0b	5.7a	6.9	0.001	1.0
Elaphonema spp.		28.5a	1.2b	1.3b	8.4	<0.001	19.4
FLN		363.3ab	288.5b	546.5a	5.6	0.005	185.1
Fungivores		88.5b	84.1b	157.6a	4.8	0.009	59.8
Helicotylenchus spp.		125.5a	72.1ab	34.1b	3.9	0.023	77.8
Panagrolaimus spp.		6.1b	5.8b	59.5a	3.4	0.035	51.6
Paratrichodorus spp.		0.6b	1.8b	9.9a	7.7	0.001	5.6
Rotylenchus spp.		89.5a	20.6b	22.1b	8.3	<0.001	49.1
Total nematodes		684.5ab	448.3b	901.3a	8.0	<0.001	275.2
Total taxa		10.1ab	9.2b	11.7a	5.1	0.007	1.9
Tylenchus spp.		35.9b	42.1b	93.1a	6.1	0.003	39.4
Xiphinema spp.		5.9a	0.4b	0.3b	4.6	0.011	5.4
Elaphonema spp.	% of trophic group	7.2a	0.6b	0.3b	11.5	<0.001	4.1
Panagrolaimus spp.		2.6b	2.2b	7.4a	3.6	0.030	4.7
Paratrichodorus spp.		0.7b	1.3b	8.2a	8.3	<0.001	4.5
Pratylenchus spp.		7.4b	14.1ab	17.4a	3.2	0.043	9.7
Cephalobus spp.	% of total population	4.0b	8.2a	2.5b	6.7	0.002	3.9
c-p 3		42.3a	35.9ab	29.7b	3.4	0.035	11.3
c-p 3-5		49.8a	41.6ab	36.8b	3.9	0.022	11.2
Elaphonema spp.		3.1a	0.1b	0.1b	8.8	<0.001	2.1
Fungivores		12.8b	17.8ab	21.3a	3.9	0.022	7.2
Panagrolaimus spp.		1.3ab	0.7b	3.4a	3.6	0.029	2.3
Paratrichodorus spp.		0.1b	0.3b	1.3a	8.2	<0.001	0.7
Tylenchus spp.		5.4b	8.9ab	11.5a	3.9	0.021	5.1
Xiphinema spp.		2.1a	0.2ab	0.0b	3.8	0.025	2.1
Basal Index	Index	67.1a	62.0ab	59.3b	3.4	0.037	7.4
Enrichment Index		32.8b	41.7b	52.2a	9.7	<0.001	10.1

[a] c-p: colonizer-persister class; FLN: free-living nematodes (excluding all plant-parasites); NH_4^+ (T7): soil NH_4^+ after 7 days of anaerobic incubation; PMN: potentially mineralizable nitrogen. PPN: plant-parasitic nematodes. [b] Means in a row followed by the same letter do not differ significantly at $P \leq 0.05$ based on pairwise comparisons with Tukey's Honestly Significant Difference test [c] Only significant results for soil disturbance effects are shown; variables with significant F-values by region and interactions were omitted

Plant-available P (Bray I) was higher in the cultivated soils than in either the natural or pre-plant soils (F = 29.1, P < 0.001). The PMN was significantly higher in the undisturbed natural soils than in either the disturbed or cultivated soils.

Of the plant-parasitic nematodes, *Pratylenchus* spp. and *Paratrichodorus* spp. numbers were substantially higher in the cultivated soils, whereas *Rotylenchus* spp. and *Xiphinema* spp. numbers were significantly higher in the undisturbed natural soils than either the disturbed or the soils containing tomato plants. *Helicotylenchus* spp. numbers were significantly higher in the undisturbed natural soils than the post-plant soils only.

The abundance (% of the total population) of specific FLN genera was linked to the specific soil disturbance types. *Elaphonema* spp. were abundant in the natural soils, but not in the pre-plant and cultivated soils. On the other hand, *Panagrolaimus* spp. were more abundant in the cultivated soils than the natural or pre-plant soils. *Cephalobus* spp. were abundant only in the disturbed soils.

From a soil food web perspective, nematodes are sensitive indicators of soil disturbance. The total numbers of nematodes were highest in the cultivated soils and lowest in the pre-plant soils. The enrichment index (EI), the number of bacterivores and fungivores, and the number of bacterivore taxa were higher in the cultivated soils, while the basal index (BI) was highest in the natural soils. The proportion of cp 3 and c-p 3-5 nematodes were lower in the cultivated than the natural or pre-plant soils.

Two-way ANOVA was used to identify secondary indicators of soil health/quality based on significant differences based on soil disturbance and region respectively, but without significant soil disturbance and region interactions (Table 7.5). Therefore, these secondary indicators still responded to soil disturbance, but the magnitude of the responses varied significantly between production regions based on the ecological constraints associated with each bioregion.

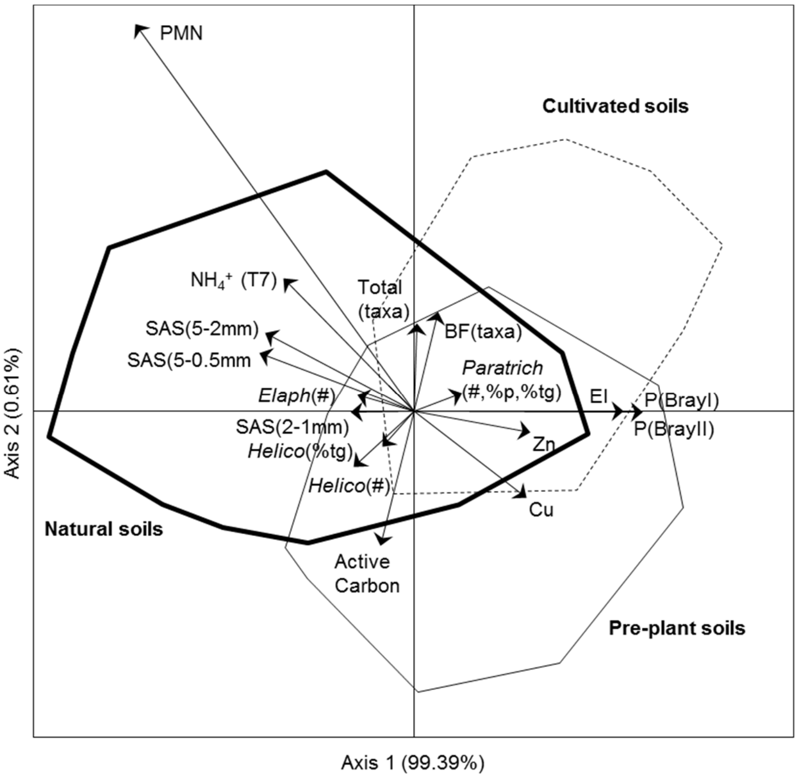
TABLE 7.5: Secondary soil quality indicators in the Limpopo tomato production region of South Africa

Variable[a]	**Unit**	**Soil disturbance**[b]			**ANOVA**[c]				
					Soil disturbance		**Region**		**Tukey's**
		Natural	**Pre-plant**	**Cultivated**	**F-value**	**P-value**	**F-value**	**P-value**	**LSD**
Active carbon	ppm	548.2a	711.5a	166.8b	22.7	<0.001	4.3	0.015	187.8
Cu		5.1b	8.2a	6.5b	14.7	<0.001	15.0	<0.001	1.7
P (Bray II)		42.8b	68.4b	111.9a	22.3	<0.001	12.3	<0.001	28.9
Zn		2.5b	3.6a	3.7a	7.8	0.001	4.1	0.018	0.9
pH	pH	5.4b	5.9b	6.1a	18.3	<0.001	50.5	<0.001	0.3
CEC	cmol$^+$ kg^{-1}	7.2a	8.0a	5.2b	9.9	<0.001	12.4	<0.001	1.5
SAS (0.5-5 mm)	%	16.4a	8.5b	8.3b	19.5	<0.001	14.5	<0.001	3.9
SAS (1-2 mm)		2.1a	1.2b	0.9b	5.4	0.005	5.2	0.006	0.9
SAS (2-5 mm)		11.9a	5.9b	6.5b	17.2	<0.001	10.7	<0.001	3.0
Plant-parasitic nematodes	numbers 250 cc^{-1} soil	321.2b	158.7c	728.7a	6.0	0.003	3.6	0.030	149.5
Helicotylenchus spp.	% of population	18.3a	14.9ab	6.2b	4.0	0.019	4.1	0.018	9.8
Rotylenchus spp.		11.2a	5.2ab	3.3b	5.2	0.007	3.6	0.028	6.3
Helicotylenchus spp.	% of trophic group	35.4a	31.8a	12.4b	5.6	0.005	6.7	0.002	16.6

[a] CEC: cation exchange capacity; SAS: soil aggregate stability for different mean weight diameter class. [b] Means in a row followed by the same letter do not differ significantly at $P \leq 0.05$ based on pairwise comparisons with Tukey's Honestly Significant Difference test. [c] Only significant results for soil disturbance and region differences are shown; variables with significant soil disturbance x region interactions were omitted

Soil chemistry and physical variables featured prominently in the set of secondary soil health indicators (Table 7.5). Soil pH and P (Bray II) were higher in the cultivated than in the natural or pre-plant soils. Soil Zn was significantly lower in the natural than in the pre-plant and cultivated soils. Active carbon levels were significantly lower in the cultivated soils than the natural or disturbed soils. The aggregate stability of the larger size fractions (0.5-5 mm and 2-5 mm) was very sensitive to the physical disruption associated with the land preparation stage; the SAS values did not differ significantly between pre-plant and cultivated soils. Of the plant-parasitic nematodes, *Helicotylenchus* spp. (% of the total population and the trophic group) and *Rotylenchus* spp. were significantly more abundant in the natural than the cultivated soils, but not the pre-plant soils, while the total number of the plant-parasitic nematodes was significantly higher in the cultivated than the natural or disturbed soils.

MANOVA results confirmed the sensitivity of PMN, NH_4^+ (T7), SAS, P (Bray I and II) and the EI to soil disturbance (Fig. 7.2).

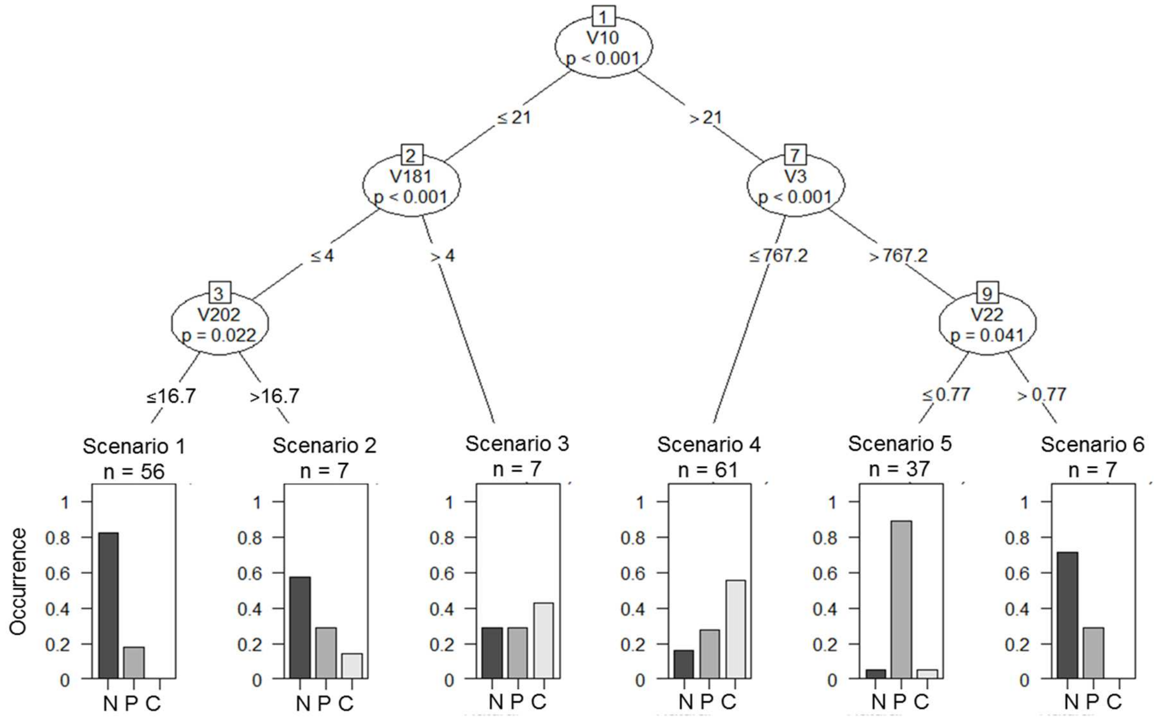


The remaining variables clustered around the centre of the graph and were omitted to facilitate interpretation of the graph. Key: #: numbers cm^{-3} soil. % p: proportion of total nematode population. # tg: proportion of trophic group. EI: enrichment index. NH_4^+ (T7): ammonium after 7 days of anaerobic incubation. PMN: potentially mineralizable nitrogen. SAS: soil aggregate stability.

FIG. 7.2: Multivariate analysis of variance results indicate most important variables for describing soil quality in the tomato production region

MANOVA results did not provide supporting for considering active carbon, *Helicotylenchus* spp. and *Paratrichodorus* spp. as candidate indicators of soil health associated with soil disturbance in the tomato production context of this study.

CART analysis was used to identify the combination of soil quality indicators that discerned between different soil disturbance types (Fig. 7.3). According to CART analysis results, natural soils had low levels of nutrient enrichment as evidenced by low levels in available P, the c-p 1 bacteria-feeding *Mesorhabditis* spp. and the c-p 2 fungal-feeding *Aphelenchus* spp. (scenario 1 in Fig. 7.3). However, in scenarios where P (Bray I) was high, high levels of active carbon and soil carbon were characteristic of natural soils (scenario 6). The carbon level in disturbed soils did not exceed 0.77 %, even though the active carbon levels were higher due to enhanced microbial activity in response to decomposition of organic matter and exposure of particulate organic matter upon tillage (scenario 5). It was more difficult to clearly identify the variables associated with cultivated soils other than the high available inorganic P (Bray I) and low active carbon in scenario 4, or the low available inorganic P and a marginally higher abundance of enrichment opportunists such as *Mesorhabditis* spp. (scenario 3).



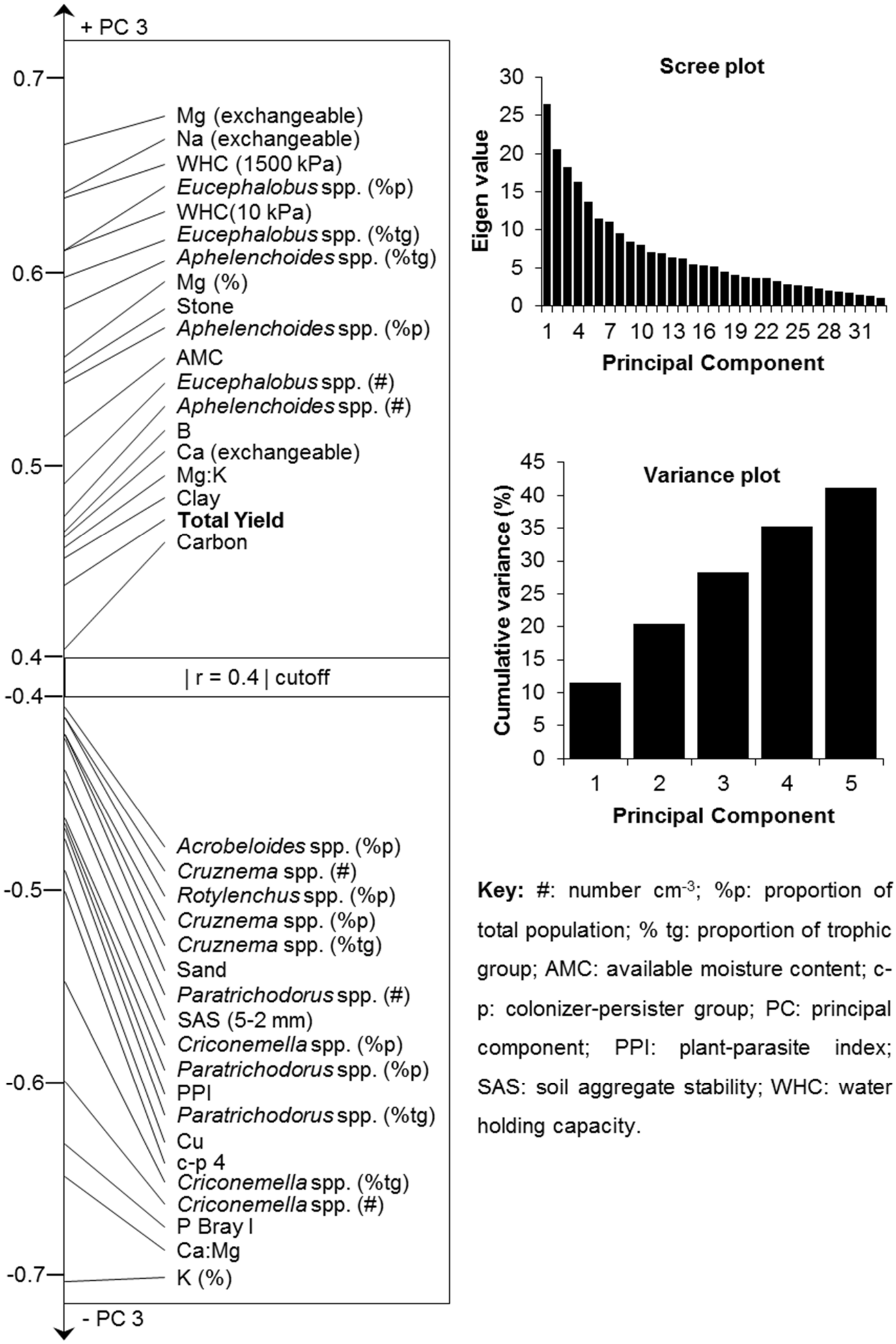
Key: V3: Active carbon (ppm); V10: P (Bray I, mg kg^{-1}); V22: Carbon (%); V181: *Mesorhabditis* spp. (% of total population); V202: *Aphelenchus* spp. (% of total population). All splits and levels are shown.

FIG. 7.3: CART analysis results indicate the combination of variables that explain significant differences between natural (N), pre-plant (P) and cultivated (C) soils

7.3.2 Tomato yield

The correlation between soil health indicators and tomato yield was explored in two datasets: prepared soils (n = 50) and cultivated soils (n = 40). Data for all the production regions were pooled to determine the main statistical trends. Correlation analysis, CART and PCA did not demonstrate any associations between soil health variables from the prepared soils and tomato yield.

For the cultivated soils dataset, PCA was used to explore the interaction between specific soil health variables and total yield. According to the eigenvalue > 1 rule, > 33 significant PCs had to be retained for further analysis, but the >5% variance guideline reduced this requirement to the first five PCs. The first PC explained only 11.5% of the variance, and the next four PCs another 8.9%, 7.9%, 7.0% and 5.9% respectively (a total of 41.2% variation). Soil health variables correlated with total yield only on PC 3 (Fig. 7.4).



Key: #: number cm^{-3}; %p: proportion of total population; % tg: proportion of trophic group; AMC: available moisture content; c-p: colonizer-persister group; PC: principal component; PPI: plant-parasite index; SAS: soil aggregate stability; WHC: water holding capacity.

FIG. 7.4: Graphical summary of the correlation between soil biological, chemical and physical variables and tomato yield according to principal component analysis

The soil chemical and physical variables dominated PC3, followed by the soil biological variables to a lesser extent. According to PC3, tomato yield was a function of suitable soil structure (caused by the balance between exchangeable Ca, K, Mg, and Na), optimum soil moisture relations (WHC and AMC), and presence/absence of specific yield-limiting PPN genera, soil texture and organic carbon content (Fig. 7.4).

The PCA results were used to construct a quantitative yield prediction model based on multivariate regression analysis (Table 7.6; Fig. 7.5). The model contained 34 variables associated with nematode community profiling (18), soil chemistry (10) and soil physical (6) characteristics. The predictive capability of this model is satisfactory with an $R^2 = 0.997$. However, the model is very complex and designed within a specific South African tomato production context and may not find application in the wider tomato production framework.

Seven specific nematode genera featured prominently in the regression model: three bacterivores (*Acrobeles* spp., *Cruznema* spp. and *Eucephalobus* spp.), one fungivore (*Aphelenchoides* spp.) and three plant parasites (*Criconemella* spp., *Paratrichodorus* spp. and *Rotylenchus* spp.). The total numbers, proportion of the total population and proportion of the trophic group were important variables for several of the nematode genera mentioned. Of the range of NCP indices evaluated in this study, only the proportion of c-p 4 nematodes and the PPI were associated with tomato yield variation. The low R^2 values for most of the nematode variables bring into question their relative importance to the final yield prediction model. Yet omitting these variables reduced substantially the overall R^2 of the model ($R^2 < 0.5$, data not shown), thus indicating these variables influence tomato yield directly or indirectly.

The variables associated with the soil macro elements (Ca, Mg, K and available P) dominated the soil chemistry component of the regression model. Boron and copper were the only micro elements associated with tomato yield variation in this study. The soil carbon content and six soil physical variables were also relevant to the successful predictive power of the regression model.

TABLE 7.6: Descriptive statistics of linear regression model for predicting tomato yield based on the biological, chemical and physical characteristics of the cultivated soils

Linear model components[a]	**Coeff.**	**SE**	**P-value**	**R^2**	**Linear model components**	**Coeff.**	**SE**	**P-value**	**R^2**
Constant	6769.8	746.9	<0.001						
Soil biological variables[b]					**Soil chemical variables**				
Acrobeles spp. (% p)	34.9	12.1	0.034	0.072	Boron	-220.8	29.5	0.001	0.253
Aphelenchoides spp. (#)	136.3	19.6	0.001	<0.001	Carbon	-752.2	81.7	<0.001	0.002
Aphelenchoides spp. (% p)	-2151.0	247.0	<0.001	0.004	Ca:Mg	76.7	6.7	<0.001	0.045
Aphelenchoides spp. (% tg)	759.3	87.8	<0.001	0.007	Copper	45.9	4.6	<0.001	0.195
c-p 4 nematodes (% p)	384.9	50.6	0.001	0.095	Calcium (mg kg^{-1})	-1.3	0.1	<0.001	0.142
Criconemella spp. (#)	-384.5	41.2	<0.001	0.232	Magnesium (mg kg^{-1})	4.8	0.5	<0.001	0.060
Criconemella spp. (% p)	-5840.5	608.0	<0.001	0.072	Sodium (mg kg^{-1})	-1.0	0.1	<0.001	0.118
Criconemella spp. (% tg)	3983.3	424.2	<0.001	0.120	Potassium (%)	-102.9	9.0	<0.001	0.155
Cruznema spp. (#)	-334.4	32.2	<0.001	0.061	Mg:K	-294.5	27.0	<0.001	0.013
Cruznema spp. (% p)	10421.0	1216.4	<0.001	0.073	P(Bray I)	-3.4	0.4	<0.001	0.073
Cruznema spp. (% tg)	-5322.0	714.1	0.001	0.069					
Eucephalobus spp. (#)	-221.0	25.7	<0.001	0.002	**Soil physical variables**				
Eucephalobus spp. (%p)	-2733.1	328.6	<0.001	<0.001	AMC	15.4	1.6	<0.001	0.033
Eucephalobus spp. (%tg)	3191.5	360.6	<0.001	<0.001	Clay (%)	-55.7	6.4	<0.001	0.005
Paratrichodorus spp. (% p)	810.7	65.1	<0.001	0.049	Sand (%)	-58.3	6.8	<0.001	0.002
Paratrichodorus spp. (% tg)	-646.0	53.6	<0.001	0.119	SAS (2-5mm)	5.7	1.3	0.006	0.298
PPI	-30.0	5.7	0.003	0.243	Stone	11.2	1.3	<0.001	0.065
Rotylenchus spp. (% p)	111.9	15.5	0.001	0.147	WHC (1500kPa)	-10.2	1.1	<0.001	<0.001

[a]. Transformed values used in regression model. [b]. #: number cm^{-3}; % p: proportion of the total nematode population; % tg: proportion of the trophic group; AMC: available moisture content; Coeff.: coefficient; PPI: plant-parasitic index; SAS: soil aggregate stability; SEM: Standard error of the mean; WHC: water holding capacity

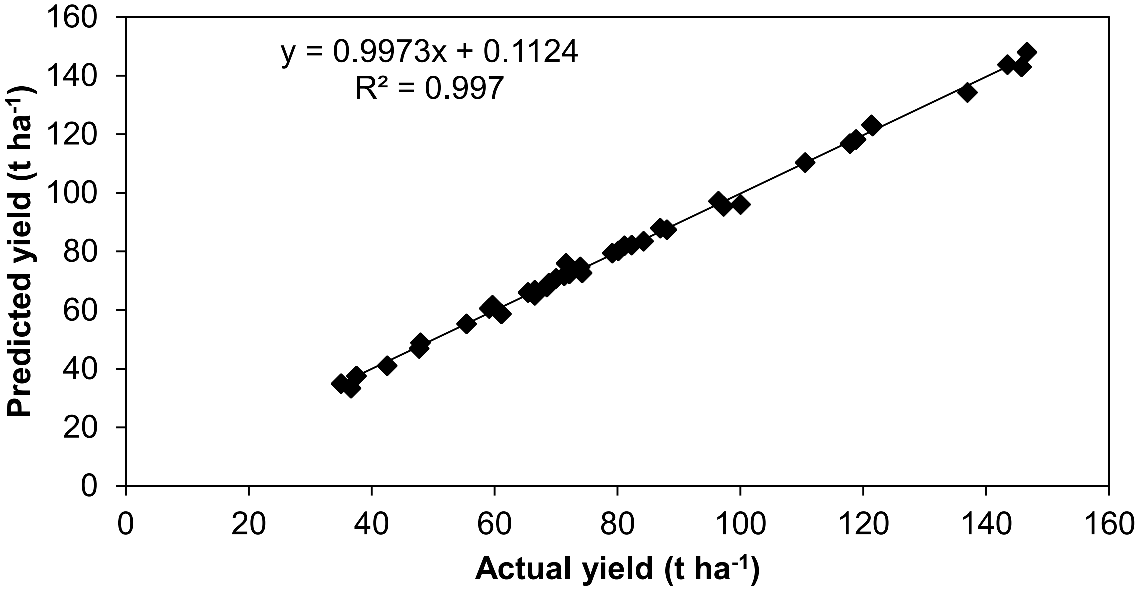


FIG. 7.5: Tomato yield prediction based on the biological, chemical and physical characteristics of the cultivated soils

7.4 Discussion

7.4.1 Soil health indicators

The objective of this study was to identify soil health indicators suitable for testing at resource-limited on-farm soil testing laboratories. The results of this study suggests that PMN, active carbon, soil aggregate stability, extractable P, and selected nematode community profiling variables are suitable soil health indicators for the tomato production region studied.

7.4.1.1 Potentially Mineralizable Nitrogen

Nitrogen availability is a key soil health indictor and features in many soil health testing initiatives and sustainable agriculture studies (Schloter et al. 2003, Bini et al. 2014). The anaerobic and aerobic versions of the basic PMN test are sensitive indicators of N-mineralization in the agro-ecological context (Knoepp et al. 2000, Becker and Johnson 2001, Benintende et al. 2008, Postma et al. 2008, Peigne et al. 2009, Jangid et al. 2010, Marzaioli et al. 2010). Indicators associated with N cycling are sensitive to land use change and crop management (Bini et al. 2014). The results of this study confirm the robustness of the anaerobic PMN test for soil health testing at the regional scale.

Although several methodological variations of the test exist (i.e., aerobic vs anaerobic, incubation time from 24 h to 60 d), the method is a robust indicator of soil health because N-mineralization is effected by a wide range of soil microorganisms. Therefore, the PMN test serves as proxy indicator of soil microbial activity (Schindelbeck et al. 2008, Ekelund et al. 2009) and correlates well with classic soil microbial activity metrics such as the soil organic C content, soil N, microbial biomass, microbial biomass N, and fluorescein-diacetate activity (Myrold 1987, Benintende et al. 2008, Peigne et al. 2009). For example, biological disease suppression in soils is often linked to microbial activity and Postma et al. (2008) correlated suppression of *Verticillium* in organic soils from The Netherlands with aerobic PMN.

Negative PMN values were observed in our dataset and were reported by others as well (Myrold and Posavatz 2007, Chaer et al. 2009). This is an indication that aerobic incubation occurred because NH_4^+ is converted to NO_3^- through microbial action (Marchetti et al. 2008). However, we took every precaution to prevent this from happening in the laboratory. Literature indicates that low or negative PMN values are obtained from soils with very high C:N ratios (>30) (Chaer et al. 2009). Since microbial activity and N-mineralization depends on carbon availability, the PMN test result is therefore indicative of organic matter quality and availability (Myrold and Tiedje 1985, Becker and Johnson 2001). This explains the decline in PMN during the pre-plant stage because of active organic matter decomposition that follows land clearing and ridging activities.

7.4.1.2 Active carbon

Despite the importance of soil carbon as a soil health indicator (Knoepp et al. 2000, Bastida et al. 2008), our results indicate it is not a sensitive indicator of changes in soil management in practice. Soil carbon is a sensitive indicator of deteriorating soil quality (Beheshti et al. 2012, Bruun et al. 2013, Swanepoel et al. 2014), but not sensitive enough as soil management indicator because it increases very slowly over time (Kahlon et al. 2013, McGovern et al. 2013, Turner et al. 2014). For this reason, research efforts focus on analysing the labile, 'dissolved', or 'active' carbon fractions of the total carbon pool. Indeed, labile carbon is a critical component of various soil physical (i.e., soil aggregate formation), chemical (i.e., nutrient availability) and biological (i.e., microbial activity) processes (Van Antwerpen 2005).

Active carbon is a sensitive and robust soil quality indicator in the international agro-ecological context (Murage et al. 2000, Becker and Johnson 2001, Pattison et al. 2008, Culman et al. 2010, Culman et al. 2012, Plaza-Bonilla et al. 2014, Schipanski et al. 2014, Benbi et al. 2015). The method was useful for comparing undisturbed soils with pasture soils in South Africa (Swanepoel et al. 2014). Active carbon also correlates well with other soil microbial activity or biomass indicators (Culman et al. 2012) as well as soil macro-aggregate content (Jha et al. 2012). For this reason, permanganate oxidizable carbon may be used as a leading soil health indicator (Bruun et al. 2013), especially when organic soil or crop management technologies are used by producers (Kamble and Bååth 2014). The major benefits of the active carbon method of Weil et al. (2003) are cost-effectiveness, moderate technology requirements, and low trained labour requirement, and ease of interpretation (Bruun et al. 2013). The avoidance of dealing with chromium-wastes from the Walkley-Black method is another benefit, although disposal of large volumes of $KMnO_4$ waste may pose similar challenges to the use of the method in future.

The active carbon test has some disadvantages. Similar to the Walkley-Black test, the active carbon procedure provides a broad and often poorly defined description of an important soil quality feature (e.g., soil carbon). These tests may be 'overwhelmed' or 'decoyed' by the presence of labile carbon, thus masking a potentially important result regarding the long-term structural integrity of the soil organo-mineral complex. For example, the Walkley-Black carbon content of the soils from the Central Bushveld region did not differ significantly ($P > 0.10$) between the preparation and cultivation soil management samples (Table 7.3). However, the CEC changed substantially for this dataset: the CEC was 34% less in the cultivated than the natural or prepared soils. The soil CEC is a measure of soil quality because it describes, among other things, the nutrient storage potential of the soil. The relationship between the soil CEC and the C content is linear and positively correlated (e.g., Sinoga et al. 2012), which makes the apparent decline of the CEC observed in the tomato production region (Table 7.5) all the more alarming, especially after nine years of practising ZZ2-Natuurboerdery®.

7.4.1.3 Aggregate stability

Soil aggregate stability (SAS) is a robust indicator of the negative effect of tillage on soil quality (Six and Paustian 2014). SAS decreases during soil physical disturbance (e.g., Beheshti et al. 2012) and the use of fertilizers (Graham et al. 2002). The SAS concept is critical for effective soil functioning in the crop production context. Soil organic matter fractions are protected within the various SAS size fractions (Elliott 1986, Baldock and Skjemstad 2000, Rabbi et al. 2014). Soil microbial activity is prevalent inside micro-aggregates (Bailey et al.

2012, Jha et al. 2012), but microbial N transformation is located in the macro-aggregates (Nie et al. 2014). The role of fungi in aggregate formation has long been advocated (Six et al. 2006), hence the sensitivity of both to tillage, but recent research indicates the role of fungi in maintaining aggregate integrity might be overstated (Daynes et al. 2012). Soil aggregate stability responds readily to organic matter application or soil/crop management technologies aimed at soil organic matter SOM conservation (Karami et al. 2012, Fultz et al. 2013), but the impact on C and N stocks is more prevalent on the macro-aggregates (Kong et al. 2007, Tripathi et al. 2014). However, the application of excessive quantities of K can upset the cationic base saturation equilibrium in soils and cause leaching of Ca and Mg that leads to deterioration of SAS (Auerswald et al. 1996). The results of this study are supported by others who also observed the decline of SAS in South African soils during soil management intensification (Kotze et al. 2013, Materechera 2014). Frequent burning, an activity readily pursued by South African tomato producers, is associated with deterioration of soil quality and the eventual loss of base cations in South African soils (Mills and Fey 2004).

Soil aggregate stability is a challenging research topic because aggregate formation, integrity and functionality are determined by a combination of physical, chemical, and biological factors. For this same reason, SAS is an ideal soil quality indicator for applied research or on-farm research because several important soil quality attributes are captured in a single analytical result, thus saving costs and reducing the crop producer's analytical burden.

7.4.1.4 Available soil P

The results of this study indicate extractable P (Bray I and Bray II methods) is a sensitive indicator of soil quality change. The Bray I extraction method is commonly used by South African soil testing laboratories and correlates with exchangeable Ca, pH, CEC, and clay content (Schmidt et al. 2004). Extractable P is positively associated with soil organic matter content and its management (Shen et al. 2014), whereas available P tends to decline in undisturbed soils over the long term (Turner et al. 2014). The higher P levels observed in the cultivated soils must be interpreted with care and should not be seen as a negative effect in isolation of the larger crop production objective.

The tomato crop responds readily to P synthetic fertilization or the absence thereof. Tomato root development benefits from optimum P fertilization (Garton and Widders 1990). However, P availability is limited in alkaline soils and the rate of immobilization increases with P fertilizer application rate (Fox and Kamprath 1970, Liu et al. 2011). Tomato yield response to P fertilization declines when the initial available P level is high (85 mg kg^{-1} Mehlich-1 P, Carrijo and Hochmuth 2000). Furthermore, P fertilization enhances root-knot nematode (*Meloidogyne* spp.) damage (Mahmood et al. 2011). Thus, the increase in soil P is an expected outcome of fertilization associated with crop production. However, the accumulation of P to beyond growth-limiting levels is cause for concern, which further supports its inclusion in a soil health minimum dataset for the South African tomato production context.

7.4.1.5 Nematodes

Nematode community profiling is an effective tool for describing soil disturbance and tomato yield variation. The results reported in this study corroborate the results and discussion of Chapter 6 and will not be repeated here.

7.4.2 Soil health vs. crop productivity

The South African tomato producers in this study are aware of the need to follow sustainable production practices in order to maintain long-term soil productivity. In scientific literature, the correlations between soil quality indicators and crop yield are often low (but not absent) (e.g., Li et al. 2013). This is because additional biotic and abiotic factors not included in the statistical analysis influence crop productivity. PCA and regression analysis confirmed that tomato yield variation in this South African case study was explained by a complex combination of several soil biological, chemical and physical characteristics.

Soil nematodes, both free-living and plant-parasitic, dominated the tomato yield prediction model. The bacterivorous *Cruznema* spp. and *Eucephalobus* spp. and fungivorus *Aphelenchoides* spp. respond readily to organic nutrient enrichment (Renčo et al. 2010, Zhao and Neher 2013). These nematodes responded to the South African tomato producers’ usage of compost, manures and additional organic and synthetic fertilizers. Other studies correlated *Aphelenchoides* spp. positively with non-toxic levels of copper in the soil (Zhao and Neher 2013) but we did not observe this in our dataset (data not shown). Although the impact of plant-parasitic nematodes on crop yield is well-described in the literature, more research is needed to improve our understanding of the effect of individual free-living nematode genera on tomato crop productivity. This study also highlighted the importance of the balance of each genus in relation to the total population and that of the trophic group as opposed to focussing on only threshold levels based on the numbers of nematodes.

Soil organic matter management is a key strategy for improving and maintaining soil quality. The South African tomato producers of this study managed the soil organic matter content with compost and manures. However, the results of this study indicate that soil carbon was very poorly correlated to tomato yield and only in the multivariate context (Fig. 7.4). Thus, although organic matter additions improve soil health, whether it translates into improved crop yields remains a complex issue (e.g., D'Hose et al. 2014, Kätterer et al. 2014, Marinari et al. 2015). Organic matter additions can complicate soil quality by importing excessive salinity and nutrients, and reduce soil functioning (Al-Busaidi et al. 2014). Soil biology - whether micro- and macroscopic - can effectively compete with plants for nutrients (Kirkby et al. 2013, Toyota et al. 2013). Adding manures and composts to soils can foster antibiotic-resistant populations which may threaten human health in the wider context (Cytryn 2013). Finally, prevailing climate conditions dominate crop responses to organic crop and soil management (Marinari et al. 2015). In this study, water holding capacity, available moisture capacity, and clay and sand content - each associated with good soil quality irrespective of the soil's carbon content - were components of the regression model.

Boron and copper are important components of tomato micro element fertilization and excessive or insufficient levels cause yield and quality problems (Rhoads et al. 1989, Ben-Gal and Shani 2002, Davis et al. 2003). In this South African case study, soil boron levels were not excessive, which explains the positive and linear association with tomato yield. The importance of calcium fertilization to prevent tomato quality problems is well described in the scientific literature. The results of this study confirm this aspect of tomato macro nutrient fertilization requirements.

The complexity of applying soil health principles in practice is exemplified by the negative, but counter-intuitive association of high SAS (2-5 mm) and low tomato yield (Fig 7.4). As stated earlier, SAS is a key soil health indicator. However, in this tomato production context it was negatively correlated with tomato yield. Furthermore, PCA indicated that exchangeable K was also associated with low tomato yield. How can this be possible if SAS is a key soil health indicator and K nutrition a critical component of tomato yield and quality?

The integrity of the soil aggregate depends on the interaction and balance between the major soil cation species: Ca, K, Mg, and Na. Levy and Torrento (1995) indicated that increasing the exchangeable K content from 10 to 15% in clay soils did not affect macro-aggregate stability. Organic K (potassium humate) improves soil macro-aggregate (2-5 mm) stability, but the effect is highly dependent on soil pH (Imbufe et al. 2005). The application of K fertilizer, and the resultant negative effect on the exchangeable Ca and Mg content, was implicated in SAS deterioration in soils from Europe (Pernes-Debuyser and Tessier 2004) and South Africa (Levy and Van der Watt 1990, Graham et al. 2002). The resultant collapse of the colloidal matrix decreases infiltration and hydraulic conductivity of soils (Chen et al. 1983); this is confirmed by the opposite relationship between soil K, WHC and AMC as indicated by the PCA results (Fig. 7.4). This poses a significant challenge to tomato producers in South Africa because K plays a crucial part in tomato crop health and its fertilization requirement is often two- to three-fold higher than that of N (Gould 1992, Hartz et al. 1999).

Exchangeable soil K content is not the only important soil health indicator with relevance to aggregate stability and tomato yield. Zhang et al. (2013) reported that the macro-aggregates (>2 mm) contained more nematodes than the micro-aggregates, regardless of the trophic group (Zhang et al. 2013). *Paratrichodorus* spp. belongs to the fourth colonizer-persister class, which means these nematodes are physically large and sensitive to disturbance. These ecological characteristics enable the nematodes from this genus to thrive in the larger pore spaces offered by the macro-aggregate environment.

The results of this study suggest that K-mediated colloidal collapse and/or the presence of specific plant-parasitic genera contributed possibly to lower yield in the South African tomato production region studied. The regression-based yield prediction model indicates complex interactions between biotic and abiotic factors explain tomato yield variation in the tomato production system studied.

7.5 Conclusion

The objective of this study was to find soil health or soil quality indicators suitable for on-farm testing in a resource-limited laboratory set-up. This study identified PMN, active carbon, SAS, nematode community profiling, and available soil P as robust soil health indicators of soil quality change in the Limpopo Province of South Africa. A different set of soil health indicators explained tomato yield variation, most notably boron, SAS, the balance among soil cations and the balance of specific free-living and plant-parasitic nematodes within the total population and among the trophic groups. The simplicity and universality of the soil health concept is challenged by the association of low tomato yield with the presence of ecto-parasitic nematodes (*Criconemella* spp. and *Paratrichodorus* spp.) in a soil of good quality (high macro-aggregate stability). Apart from the practical implications, these findings have far-reaching implications at the theoretical level. Soil health testing cannot be done in isolation of crop health considerations. The future of soil health testing will entail the simplification of analysing key soil quality variables on the one hand, while its complexity will increase due to the dedicated integration of these “simple tests” with the management of specific crop diseases at the molecular level of focus.

Soil health testing remains a polyphasic, crop- and context-specific endeavour. Such complexity poses a significant analytical challenge to resource-poor laboratories and producers who cultivate low-value crops. The need for relevant yet cost-effective soil health metrics remains an important research question. The information presented here will aid vegetable growers in the Southern Africa Development Corporation (SADC) region to develop region- and crop-specific soil health testing guidelines for resource-limited laboratories in rural areas.

As crop production techniques and constraint management technologies change, so too the sciences need to keep pace with these advances at the practical level. New opportunities often lead to the creation of new challenges or the re-discovery of challenges long forgotten. Good science often falls by the wayside in the fast-paced world of commercial agriculture or the cumbersome hierarchies of the government extension services. This study highlighted the importance of studying and understanding the reasons behind crop production success and failure. Advances in multivariate statistical techniques allow for closer scrutiny of very complex systems, potentially identifying novel yield-limiting or -enhancing interactions.

SUMMARY AND CONCLUSIONS

A tomato yield gap exists between tomato growers of South Africa and other SADC countries. Understanding the reasons behind tomato crop failures and successes in South Africa could boost tomato production in the fast-growing tomato markets of Angola, Mozambique and Zimbabwe, thereby improving food and nutrition security for smallholders and the population in general.

The importance of climate as yield-limiting factor is highlighted early on in this thesis (Chapter 1) and the results reported in Chapters 3 and 4 further support these observations. The realities of economics are rapidly transforming the tomato production industry in South Africa (Chapter 2), as it had done in Europe and the United States decades earlier, and more recently in Australia.

Although there is a trend to intensify open field tomato production systems to the point where protected cultivation systems become a necessity, open field production systems will remain the mainstay for millions of smallholders in South Africa and the greater SADC region. For this reason, the main findings reported in Chapters 3 and 4 have a direct bearing on small- to large-scale tomato producers. The influence of climate variation as yield-limiting variable was established. The occurrence of rain, heat, solar radiation and relative humidity were identified as critical yield-limiting climate variables. The absence of rain, non-damaging accumulation of cold units, and appropriate wind speeds were identified as yield-enhancing climate variables. The only crop management variables that mitigated yield variation associated with climate variation was the consistent use of synthetic pesticides. Within each planting window, the consistent use of synthetic fertilizers ensured high yields of high quality. Organic soil and crop management technologies featured in several high or low yield scenarios, but the incidence was low. Nevertheless, this indicated that organic soil and crop management technologies can potentially contribute to improve the sustainability of tomato production, especially where synthetic crop management technologies are not readily available to resource-limited smallholders and subsistence farmers.

Although organic crop and soil management technologies are promising alternatives to synthetic remedies, the limits of these ‘nature-friendly’ technologies have been touched upon in this thesis by means of reports from literature and circumstantial evidence (CART analyses, Chapter 4). For this reason, soil health testing is an important aspect of improving the sustainability of crop production in general, especially concerning soil quality. This thesis focussed on the usefulness of three commercially available soil biology metrics in support of sustainable tomato production in South Africa (see Chapters 5, 6, and 7).

The limit of applying ecosystem-focussed metrics to the commercial crop production context was established in this study – an observation recently confirmed by others (Rosberg et al. 2014). In short, these ecosystem-based methods are influenced in the following manner:

- Fertilizers (organic or synthetic) interfere with nutrient cycling-based methods. The crop itself secretes organic acids that facilitate nutrient release from organo-mineral complexes (Oburger et al. 2009). Understandably, the extent (but not the role) of microbial nutrient cycling in soils and its contribution to plant growth has been questioned (Chapman et al. 2006; Ryan and Kirkegaard 2012).

- Soil micro- and macroorganisms are sensitive to the application of insecticides, fungicides, bactericides, and herbicides. The selectivity and extent of these interactions are disputed due to the remarkable adaptive capacity of soil microbes, functional redundancy, and the misleading results caused by the necromass effect (Kemmit et al. 2008; Kuzyakov et al. 2009, Imfeld and Vuilleumier 2012).

- The crop itself exerts a tremendous influence on soil biological, chemical and physical environment. Active carbon readings may be influenced by root exudates, root turnover, opportunist microbial biomass flush in response to enrichment, and labile organic fractions accompanying organic matter applications.

Despite these criticisms, there is sufficient experimental evidence which suggests that benign (non-pathogenic) soil microbial factors can contribute to crop health in terms of plant growth promotion (Hariprasad et al. 2014), endo- or ectophytic disease suppression (Hariprasad et al. 2014, Romero et al. 2014), water stress tolerance (Romero et al. 2014), and cold stress tolerance (Chen et al. 2014). Soil organic matter brings all these potential ecosystem services together (Drenovsky et al. 2004). However, it remains to be seen if and when benign soil microbiology can provide these crop productivity services in the commercial tomato production context where climate variation and fertilizer and pesticide applications limit the activity and viability of these biological catalysts.

What can tomato growers in the SADC region learn from these South African tomato growers?

In short, the major factors that govern tomato yield are summarized below:

- Optimize planting times (to avoid *force majeure* climate stress).
- Optimize irrigation and manage it perfectly and intelligently (by means of appropriate technology or knowledge), because it is *that* important.
- Optimize synthetic nutrition by matching nutrient supply with crop demand.
- Optimize synthetic pest control as part of an intelligent, pest-specific, strategic integrated pest management program.
- Avoid continuous monocropping because it leads to persistent long-term soil health problems and yield reduction no matter the management system (Nayyar et al. 2009, Liiri et al. 2012, Li et al. 2014a).
- Integrate organic soil and crop management techniques or technologies as far as possible, not for the purpose of replacing synthetic crop nutrition and protection systems, but to augment soil quality management and root health.
- Choose the best cultivar for the bioregion and keep on looking for cultivars that can support the main cultivar or provide better resilience around the risky fringes (start and end) of the optimum planting window (e.g., early maturing, cold or heat resistant, etc.).

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