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Ecophysiological and Agronomic Response of Abaca (*Musa textilis*) to Different Resource Conditions in Leyte Island, Philippines

Dissertation

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Statement of Uniqueness

AUTHOR'S DECLARATION

I, Marlito M. Bande, hereby affirm that I have written this thesis entitled **"Ecophysiological and Agronomic Response of Abaca (*Musa textilis*) to Different Resource Conditions in Leyte Island, Philippines"** independently and entirely as my original work as part of my dissertation at the Faculty of Agricultural Sciences at the University of Hohenheim.

All the authors in all the publications that are quoted or mentioned in this manuscript have been credited. No piece of work by any person has been included without the author being cited, nor have I listed the assistance of commercial promotion agencies.

This dissertation, or part of it, has not been submitted to any other boards for examination.

Marlito M. Bande Stuttgart, 28.06.2012

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Overview of publications

In order to comply with the regulations for a cumulative PhD dissertation at the Faculty of Agricultural Sciences, several publications have been included into this work. As these publications have been edited to fit the regulations of different publishers, the style for quoting and the layout of the reference section may vary between chapters.

Chapter 2

Marlito M. Bande, Jan Grenz, Victor B. Asio and Joachim Sauerborn (expected 2013). Morphological and Physiological Response of Abaca (*Musa textilis* var. *Laylay*) to Shade, Irrigation and Fertilizer Application at Different Stages of Plant Growth. Journal of Natural Fibers, (in review).

Chapter 3

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Chapter 4

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1. General Introduction

1.1 Ecology and distribution of abaca plant

Abaca (*Musa textilis* Née) is closely related to edible banana (*Musa acuminata* and *M. balbisiana*) that is indigenous to the understorey of the Philippines' tropical lowland evergreen rainforests (Tabora Jr., 1978; Halos, 2008; Sievert, 2009). It is grown primarily for its fibers. The plant requires specific climatic and soil conditions; hence, its cultivation is limited to defined regions (McCreery, 1960). Abaca grows best on a fertile soil of recent volcanic or alluvial origin with good moisture retention (Spencer, 1953; Umali and Brewbaker, 1956; Tabora Jr. and Santos, 1978), rainfall of 2000 – 3000 mm year^{-1}, no dry season, humidity range of 78-88%, optimum temperature range of 20-27 °C (Halos, 2008) and at altitudes up to 1,000 meters (Sievert, 2009).

The abaca plant was first described by Don Luis Née (1801) who gave the earliest confirmation that abaca is indigenous to the Philippines. According to Spencer (1953) and Tabora Jr. (1978), the earliest account on the use of abaca was written by *Pigafetta* the Spanish priest who chronicled the voyage of Magellan in 1521, where he observed that the natives in Cebu Island were already wearing clothes made from the fiber of the abaca plant as early as the 16th century.

The Philippines is the center of origin of abaca (Halos, 2008; Lalusin 2010) from where it then moved southward to Borneo (Spencer, 1953; Umali and Brewbaker, 1956). Valmayor et al. (2002) reported that the Philippines have six indigenous species of *Musaceae* (including abaca). The abaca germplasm found in other parts of the world today can be traced back to the Philippines where in fact, the varieties planted carry the same names in the country (Halos, 2008). Historical records showed that an American lieutenant of the US Navy brought abaca fiber to the United States in 1820 (Lalusin, 2010).

Furthermore, Copeland (1911) reported that the crop was introduced in India (1822), Borneo, East Africa, West Indies and Florida but were unsuccessful or not commercially viable. Spencer (1953) and Dempsey (1963) documented that the US government introduced abaca in Latin American countries (i.e., Panama, Ecuador, Costa Rica, Guatamela, Honduras, Dominican Republic, Brazil, British and French Guiana, Cuba, Jamaica, Puerto Rico, Martinique, Guadeloupe, Trinidad, Mexico, St. Vincent, Bolivia, Peru, Nicaragua and El Salvador) in 1923.

In 1925, abaca seed pieces from the Philippines were also used to establish plantations in Sumatra, British Borneo and Malaya (Lalusin, 2010) and in New Caledonia and Queensland, Australia (Torres and Garrido, 1939). After World War II, a Japanese owner of abaca plantation in Davao, Philippines, started field testing and successfully cultivated abaca in Ecuador which produces abaca fiber for export and presently supplies 16% of the world market (Lalusin, 2010).

1.2 Importance of abaca in the Philippine economy

Abaca rope has been one of the major exports of the Philippines since 1825 (Tabora Jr., 1978). This was after the American Navy discovered that abaca was an excellent material for marine cordage (Constantino, 1975) due to its superior tensile strength and proven durability under seawater (Lalusin, 2010). The opening of two ports – one in Legazpi, Albay and another in Tacloban, Leyte – to international shipping in 1873 was another boost to the abaca industry in the Visayas: farmers in Cebu, Samar and Leyte started establishing their abaca farms (Constantino, 1975). On the other hand, Ynchausti y Compaña, a Spanish firm, maintained a rope factory in *Balut*, *Tondo*, *Manila* and got their raw materials from *Sorsogon, Bicol Region*. This started the clearing of virgin forestlands in the province to give way to the abaca plantations (Constantino, 1975). Since 1909, Americans began to venture into abaca trading and established plantations in Davao. Edwards (1945) reported that Japan also became interested in abaca for its navy, and chose Davao as their plantation site. However, the use of nylon for cordage had greatly reduced the market for this product, to the extent that it had placed the entire abaca industry in danger of collapsing during the 1960s and 1970s (PCARRD, 1971).

Despite this setback, abaca experienced a revival in the world market when alternative uses of abaca wastes were discovered for processing of specialty papers. Presently, it remains a potent export crop because of its wide range of uses particularly in the manufacture of tea bags, sausage casings, currency notes, cigarette filter papers, wire cable installation, security paper, x-ray negatives, medical gas masks, diapers, and wire insulators, among others (Lacuna-Richman, 2002). Likewise, the specific tensile strength of the fiber is comparative or even higher than that of fiberglass (Bledzki et al., 2007; Sinon, 2008; Sinon et al., 2011). The car company, Daimler AG was successful in using abaca for the exterior parts of Mercedes-Benz A class passenger car (DaimlerChrysler, 2004; Oliver, 2004). In the United Kingdom, the use of abaca fiber as a replacement for asbestos has created a big boost in its demand (Armecin and Gabon, 2008). PCARRD (2003) reported that abaca has captured about 80% of the UK market on asbestos-based boards.

The abaca industry continues to be one of the country's major pillars in terms of employment generation and foreign exchange earnings. Lalusin (2010) reported that abaca fiber ranks 9th among the country's major agricultural exports after coconut oil, banana, pineapple, tuna, shrimps, tobacco and desiccated coconut. The industry provides livelihood to 215,130 abaca farm households (CFC-FIGHF, 2009) or to more than 1.5 million Filipinos who, directly or indirectly, depend on it for a living (FIDA 2010). From 2001 to 2010, the abaca industry generated USD82.1 million per year from the exports of raw fiber and manufactures where USD69.3 million (84.4%) of which came from abaca manufactures (i.e, pulp, cordage, yarns and fabrics and fibercrafts) and USD12.8 million (15.6%) was contributed by raw fiber exports (FIDA, 2010).

1.3 Propagation, cultivation and production of abaca

The Filipinos were first to domesticate, cultivate, process, trade and even use abaca products as an instrument in paying taxes (Lalusin, 2010). Abaca is currently cultivated in almost all provinces in the country except the Ilocos region, Cagayan Valley, Region 3, Cavite and Batangas (Halos, 2008). Abaca plants can be propagated by seeds or by vegetative cloning (i.e., sucker, corm or seed pieces, eyebud or tissue culture). Propagation by seeds were used in earlier times but are no longer used because they do not reproduce true to type and are used only for breeding work (Halos, 2008). Vegetative cloning or propagation is widely adopted (Sievert, 2009). Suckers at least one meter in height with a well developed root system have been used traditionally and are best for replanting of old plantations. Corms are used when the new plantation area is far from the source of planting materials which are used as a whole or divided into parts (referred as seed pieces). Presently, the Philippine government through the Fiber Development Authority (FIDA) promotes the use of disease-free tissue cultured planting stocks and provides the farmers with planting materials propagated through tissue culture. However, Sievert (2009) reported that tissue culture propagation is the most costly method.

The promotion and use of virus-free tissue cultured planting materials was a national strategy to control and confine the distribution and infection of the three virus diseases, i.e., abaca bunchy-top, abaca mosaic and bract mosaic virus (Sievert, 2009). Halos (2008) reported that these diseases have devastated abaca plantations since the early 20th century and caused the fluctuation in fiber supply. Raymundo et al. (2002) estimated an average incidence of abaca bunchy-top and abaca mosaic diseases in Bicol and Eastern Visayas at 5.19% and 8.16%, respectively, in 1991. Bunchy-top disease was first observed in Albay in 1911 (Ocfemia, 1926) while abaca mosaic has been known in Tagum, Davao del Norte since 1925 (Calinisan, 1934). These diseases are transmitted from abaca to abaca by aphids. The control strategy against the virus diseases remains to be vigilance in the eradication of diseased plants and use of indexed, virus-free planting materials (Halos, 2008). The application of pesticides to aphid vectors and herbicide to their weed hosts has been tried but found not very effective (Raymundo, 2000; dela Cruz, 2001; Halos, 2008; Sievert, 2009) Presently, bunchy-top and abaca mosaic are widespread in abaca-growing areas which not only reduced fiber yield but also tensile strength and farmer's income (Raymundo, 2000; dela Cruz, 2001; Halos, 2008). On the other hand, not much is known about abaca bract mosaic disease (Halos, 2008). The first natural infection of abaca with banana bract mosaic virus was reported by Sharman et al. (2000).

In developing an abaca farm, the recommended distance of planting is 2m x 2m for smaller varieties and 2.5m x 3.0m for larger varieties whether using suckers, seed pieces or tissue cultured seedlings as planting materials (FIDA, 2010). The site should include some shade trees, especially important for protecting the young plants from the sun and the older, taller plants from wind breakage. Leguminous trees are highly recommended because they do not only provide shade but also enrich the soil with nitrogen through symbiotic relationship with soil bacteria. Halos (2008) reported that annual crops are usually intercropped during plantation establishment and before the abaca canopy closes. Abaca planted as a monocrop gives significantly lower yield per hectare than those planted with annuals intercropped, e.g. legumes and cereals (Moreno, 1994). It takes 18-24 months (in fertile forestland) and 24-30 months (in open places with continuous cropping) before abaca can be harvested (Alcober, 1986; Halos, 2008; Sievert, 2009).

FIDA (2010) reported that the world consumption of abaca fibers in 2008 was 82,121 tons. The Philippines supplied 84% of the global production which is equivalent to an average fiber production of 68,982 tons yr^{-1} from 1999 to 2008, where the Eastern Visayas region (islands of Leyte, Biliran, Samar and Pana-on) was the major abaca fiber producer that supplied an annual average of 25,517 tons or 38.5% of the total production (FIDA, 2010). The average annual yield in Southern Leyte is 913 kg fiber ha^{-1}, which is above the national annual average of 610 kg ha^{-1} but far behind the potential yield of 2,000 kg of fiber ha^{-1} (PCARRD, 2001; Armecin et al., 2011). Table 1 presents the average production area and fiber yield of abaca, their percentage share and growth rates by region, 1991–2000 (PCARRD, 2001).

Table 1.1 Average production area and fiber yield of abaca, their percentage share and growth rates by region, 1991–2000

Regions	Production Area			Fiber Yield			
	10-year average (ha)	Share (%)	Growth rate (%)	10-year average (tons)	Share (%)	Growth rate (%)	Average Yield (kg ha^{-1})
Southern Tagalog	527	0.5	(3.2)	65	0.1	3.7	123
Bicol	46,882	43.1	(2.0)	21,721	32.7	0.7	463
Western Visayas	4,060	3.7	30.1	691	1.0	3.7	170
Central Visayas	2,619	2.4	1.7	266	0.4	0.3	102
Eastern Visayas	28,206	26.0	7.8	25,767	38.8	2.5	913
Western Mindanao	7,676	7.1	(0.6)	4,006	6.0	(2.8)	522
Northern Mindanao	2,919	2.7	2.7	1,708	2.6	9.0	585
Southern Mindanao	8,076	7.4	8.0	7,120	10.7	6.6	882
Central Mindanao	3,194	2.9	(1.3)	2,020	3.0	3.4	632
CARAGA	4,500	4.1	5.2	2,969	4.5	8.5	660
Total	**108,659**	**100**	**1.5**	**66,332**	**100**	**1.8**	**610**

Source: PCARRD, 2001. Values in the parentheses were regions with negative growth rates.

1.4 Abaca-based agroecosystem conditions in Leyte

In Leyte abaca plantations are grown in association with trees and coconut (Lacuna-Richman, 2002; Armecin and Gabon, 2008; Armecin et al., 2011). Only few plantations grow abaca as a monocrop. Armecin et al. (2011) reported that most of the abaca farms were intensively cultivated for more than two decades, which adversely affected crop productivity as most of the farmers never apply fertilizer in their respective farms (Photo 1).

Photo 1.1 Abaca plants grown in association with tress (*Erythrina fusca*) and coconut (*Cocos nucifera*)

Coconut, abaca and root crops planted in *kaingin*[1] had been significant components of cultivated forestlands in the island (Acosta, 1991; Dargantes, 1996). Generally, the amount of remaining forest cover can be used as an indicator of the critical situation regarding land access for the increasing number of people dependent on agriculture (Groetschel et al., 2001). The decreasing productivity and increasing instability of the island's upland resource base is reflected in the increasing poor economic status of the upland population (Stark, 2000). The adjacent lowland communities are likewise negatively affected by floods, drought and siltation (Sajise, 1986). Two concrete examples: the catastrophic flash flood in Ormoc City, Leyte on November 5, 1991 and the mudslide in Guinsaugon, St. Bernard, Southern Leyte on February 17, 2006 of which turned national and international official attention towards the tremendous problems caused by deforestation and the necessity of watershed protection.

Abaca is a shade loving crop with a good potential to be integrated into agroforestry systems (Lacuna-Richman, 2002) that offers sources of income (Dargantes, 1996) and prevents soil erosion (DENR, 1997), since it has large leaves that absorb some part of the kinetic energy of raindrops, which in turn reduces the direct impact on the soil surface (Pattison et al., 2003). In addition, abaca plants form an adventitious root system that is wide spreading, unbranched, shallow and gives rise to

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[1] Also known as *kaingin* or shifting cultivation agriculture. This process is done by clearing a patch of forest of its trees and other vegetation, allowing them to dry before burning, then planting preferred annual crop(s) on the cleared areas (SAJISE 1980 cited by GROETSCHEL 2001)

a dense mat that mechanically stabilizes the soil (Lacuna-Richman, 2002; Armecin and Gabon, 2008; Armecin et al., 2011). In integrating abaca into multi-strata agroforestry systems, one has to consider radiation interception and the efficiency with which radiation energy is used to produce photosynthates since this plays a crucial role in the growth of tree-crop stands (Balster and Marshall, 2000; Will et al., 2001; Allen et al., 2004; Kemanian et. al., 2004). Normally shading reduces photosynthesis, transpiration and partitioning of biomass from vegetative parts to economic parts (e.g. Akhter et. al., 2009). However, morphological and physiological adaptations tend to take place in response to variation in solar radiation in order to maintain maximum photosynthetic efficiency of the leaves (Duriyaprapan and Britten, 1982). A number of studies have shown that any kind of shading reduces productivity (Copeland, 1911; Stover, 1984; Israeli et al., 1994; Stanhill and Cohen, 2001; Akhter et al., 2009), while others have found that crop productivity increases under moderate shade (Boardman, 1977; Björkman and Holmgren, 1966; Holmgren, 1968; Batugal et al., 1977; Raveh et al., 2003; Isaac et al., 2007; Saifuddin et al., 2010).

1.5 Threats and problems of abaca production

Lacuna-Richman (2002) revealed that despite the importance of abaca to the national economy its potential as a source of a higher income to growers while serving as a crop that may actually help in slowing down deforestation, is given little policy attention. As a common component in traditional agroforestry systems in central Philippines, abaca is overlooked, a situation that may be ascribed to what Olofson (1983) describes as the ideological emphasis on ‘scientific’ experimental agroforestry systems, over seemingly non-scientific forest farming practices.

Promoting the benefits of abaca as an intermediate crop from slash-and-burn farmland to generate income should be considered in balance of nature and possible increase in number of households who have no livelihood option other than abaca production (Lacuna-Richman, 2002). Nishimura (1996) described local responses to limit expansion imposed on lowland farming by population increase and fragmentation of landholdings in the western Visayas, which occurred as early as 1970s. One of the common local responses was to clear land in upland forest areas for increased crop production. Leyte Island is not exempted from this phenomenon, except that at present the same natural limitations to agricultural expansion occurs even for the uplands, and there is at the same time some pressure from the government to conserve upland forest (Lacuna-Richman, 2002).

Although abaca has long been an established industry, it is still plagued with problems. Lalusin (2010) reported that areas that continue to be addressed are farm productivity and fiber quality. In Leyte, most abaca growing areas are concentrated in the hilly lands where fiber yield and quality are low (Armecin, 2008; Armecin et al., 2011). PCARRD (2003) reported that the lack of knowledge on the optimum light, nutrient and water requirements of abaca plants has greatly contributed to low fiber yield. The information available on the effects of shade and water availability on abaca growth and development is scarce, although much has been published in response to fertilizer application and on how these parameters affect biomass production and yield under field conditions where biophysical factors are very variable. To date, there are only two scientific and published reports available involving studies of abaca growth under different shade levels with conflicting results. The pioneering study of Copeland (1911) found out that growth rate and dry weight of abaca plants grown under shade were lower than those of abaca planted without shade. The second study was done by Batugal et al (1977) where they documented an improved growth and yield (variety *Tinawagang puti*) of abaca planted under partial shading at 33% and 66% than in open space.

Hence, field trials were established to study the effect of shade on the growth performance of abaca which may influence fiber yield and quality. Since abaca has high potential in multi-strata agroecological production systems, this study focuses on the ecophysiological response of the plant to shade, irrigation and fertilizer application based on the following working hypotheses: (a) shade will positively affect the ecophysiological and agronomic performance of abaca; and (b) irrigation and fertilizer application may offset the effect of shade on vegetative growth, biomass production and yield of abaca.

1.6 Objectives

The general objective of the study is to understand the effect of abiotic factors (i.e., radiation and temperature) and different management practices on the physiological performance, vegetative growth, nutrient uptake and fiber yield of abaca. The specific objectives were the following:

(a) to explore the influence of shade and irrigation-fertilization on morphological and physiological performance of abaca;
(b) to investigate the effect of reducing light intensities by 30%, 40% and 50% of full sunlight on fiber yield and fiber quality;
(c) to determine the optimum light requirement of abaca plants to attain the optimum yield without affecting the quality of the fiber for industrial use;
(d) to examine the effect of shade and irrigation-fertilization on biomass production and allocation as well as on NPK absorption and distribution among abaca organs; and
(e) to find out if irrigation and fertilization could offset the effect of shade on biomass production, NPK absorption and fiber yield of abaca.

1.7 Outline of the dissertation

Chapter 1 discusses the conceptual framework, hypotheses and objectives of the study. It also describes the ecology, history, commercial uses and importance of abaca in the Philippine economy. The knowledge and research gaps with respect to abaca propagation, cultivation, production and management are also presented in this section.

Chapter 2 presents an overview of the ecophysiological response of abaca to shade and irrigation-fertilization under different stages of growth. This chapter describes the influence of shade and irrigation-fertilization on the morphological (i.e., plant height, pseudostem length and base girth, cumulative leaf area, number of leaves effective rooting depth and number of suckers) and physiological (i.e., crop growth rate and net assimilation rate) parameters of abaca grown under different treatment combinations from seedling stage to flagleaf stage. Likewise, the negative effect of high radiation (temperature) that caused photoinhibition at seedling stage and photooxidative damage at early vegetative stage on abaca planted in full sunlight are discussed in this chapter.

Meanwhile, chapter 3 demonstrates on how shade and irrigation-fertilization treatments affect fiber yield, fiber recovery and fiber quality of abaca. This section explains the negative effect of photoinhibition on the growth parameters (i.e., pseudostem length and girth) measured that is highly correlated to fiber yield and fiber recovery of abaca. The knowledge gap on what optimum light requirement of abaca to achieve an optimum yield without affecting the quality of the fiber for industrial use is also being examined in this chapter.

Furthermore, chapter 4 illustrates the influence of different shade conditions, water and nutrient management on biomass production and allocation as well as on NPK absorption and distribution in all abaca organs from seedling to flagleaf stages of crop growth. This chapter shows a broad representation on the pattern of biomass allocation and NPK distribution among abaca organs as influenced by reduced irradiance, water and nutrient availability. It also discusses the morphological acclimations of abaca and NPK resorption or retranslocation to subsequent generations of suckers during leaf senescence.

Finally, this dissertation is concluded with general and consolidative discussion on the interconnectivity of all the results and findings presented in chapters 2 to 4. This is presented in chapter 5.

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2. Morphological and Physiological Responses of Abaca (*Musa textilis* var. *Laylay*) to Shade, Irrigation and Fertilizer Application at Different Stages of Plant Growth

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OUTLINE AND OVERVIEW

An overview of the morphological and physiological response of abaca to shade, irrigation and fertilizer application at different stages of plant growth is presented in this section. This chapter describes the influence of shade and irrigation-fertilization on the vegetative growth (i.e., plant height, pseudostem length and base girth, cumulative leaf area, number of leaves, effective rooting depth and number of suckers) and physiological (i.e., crop growth rate, leaf area ratio, net assimilation rate) parameters of abaca grown under different treatment combinations from seedling stage to flagleaf stage. Likewise, the negative effect of high radiation (temperature) that caused photoinhibition at seedling stage and photooxidative damage at early vegetative stage on abaca planted in full sunlight are discussed in this chapter.

Morphological and Physiological Response of Abaca (*Musa textilis* var. *Laylay*) to Shade, Irrigation and Fertilizer Application at Different Stages of Plant Growth

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ABSTRACT

Abaca is closely related to edible banana and grown primarily for its fibers. The information available on the effects of shade, water and nutrient availability on abaca plant physiological and vegetative growth performance under field conditions is limited. To date, there are only two scientific and published reports available involving studies of abaca growth under different irradiance and they have conflicting results. Hence, this study was carried out to investigate the effect of shade and irrigation-fertilization on abaca's morphological and physiological performance. Light infiltration was reduced by 30%, 40%, and 50% of full sunlight using polypropylene shade nets. Irrigation was applied at a rate of 5 liters plant^{-1} application^{-1} day^{-1}. Placement application of N, P_2O_5, K_2O using complete fertilizer was done at 14 grams plant^{-1} quarter^{-1} for the first six months and was increased to 40 grams plant^{-1} quarter^{-1} for the next six months after planting. Results showed that plant height, cumulative leaf area, pseudostem length and base girth of abaca significantly (probability$\leq$0.01) improved when the light was further reduced to 50%. Fertilizer application further enhanced (probability$\leq$0.05) the growth performance of abaca. Statistical analysis showed that shade and NPK fertilization positively affected dry matter production, crop growth rate, leaf area ratio and net assimilation rate from seedling to flagleaf stage. Net assimilation rate was strongly affected by shade at seedling stage and late vegetative stage (probability<0.05) due to photoinhibition. Analysis of variance showed two-factor interaction effects between shade and irrigation-fertilization on leaf area ratio at early vegetative (probability=0.016) and flagleaf (probability=0.009) stages. The superior productivity of abaca in response to shade was due to avoidance of photoinhibition and photooxidative damage that negatively affected the abaca grown under full sunlight at seedling and early vegetative stages which cannot be neutralized by irrigation and fertilizer application.

Keywords: *Musa textilis*, fiber crop, multi-storey cropping, plant growth, shade tolerance, photoinhibition, irrigation, fertilization

2.1 Introduction

Abaca (*Musa textilis* Née) is closely related to edible banana (*Musa acuminata and M. balbisiana*)) that is indigenous to the understorey of the Philippines' tropical lowland evergreen rainforests (Tabora Jr., 1978; Halos, 2008; Sievert, 2009). It is grown primarily for its fibres. The plant requires specific climatic and soil conditions; hence, its cultivation is limited to defined regions (McCreery, 1960). Abaca grows best on a fertile soil of recent volcanic or alluvial origin with good moisture retention (Spencer, 1953; Umali and Brewbaker, 1956; Tabora Jr. and Santos, 1978), rainfall of 2000 – 3000 mm year^{-1}, no dry season, humidity range of 78-88%, optimum temperature range of 20-27 °C (Halos, 2008) and at altitudes up to 1000 meters (Sievert, 2009).

Abaca plants can be propagated by seeds or by vegetative cloning (i.e., sucker, corm or seed pieces, eyebud or tissue culture). Propagation by seeds were used in earlier times but are no longer used because they do not reproduce true to type and are used only for breeding work (Halos, 2008). Vegetative cloning or propagation is widely adopted (Sievert, 2009). Suckers at least one meter in height with a well developed root system have been used traditionally and are best for replanting of old plantations. Corms are used when the new plantation area is far from the source of planting materials. Corms are used as a whole or divided into parts (referred as seed pieces). Presently, the Philippine government through the Fiber Development Authority (FIDA) promotes the use of disease-free tissue cultured planting stocks and provides the farmers with planting materials propagated through tissue culture. However, Sievert (2009) reported that tissue culture propagation is the most costly method.

In developing an abaca farm, the recommended distance of planting is 2m x 2m for smaller varieties and 2.5m x 3.0m for larger varieties whether using suckers, seed pieces or tissue cultured seedlings as planting materials (FIDA, 2010). The site should include some shade trees, especially important for protecting the young plants from the sun and the older, taller plants from wind breakage. Leguminous trees are highly recommended because they do not only provide shade but also enrich the soil with nitrogen through symbiotic relationship with soil bacteria. Halos (2008) reported that annual crops are usually intercropped during plantation establishment and before the abaca canopy closes. Abaca planted as a monocrop gives significantly lower yield than those planted with annuals intercropped, e.g. legumes and cereals (Moreno, 1994). It takes 18-24 months (in fertile forestland) and 24-30 months (in open places with continuous cropping) before abaca can be harvested (Halos, 2008).

The Philippines is the leading exporter of abaca fibre (FIDA 2010) where the majority of the abaca growing areas are situated in the hillside (Armecin and Gabon, 2008). Abaca is a shade loving crop with a good potential to be integrated into agroforestry systems (Lacuna-Richman, 2002) that offers sources of income (Dargantes, 1996) and prevents soil erosion (DENR, 1997). Integrating abaca into multi-strata agroforestry systems, one has to consider radiation interception and the efficiency with which radiation energy is used to produce photosynthates since this plays a crucial role in the growth of tree-crop stands (Balster and Marshall, 2000; Will et al., 2001; Allen et al., 2004; Kemanian et al., 2004). Normally shading reduces photosynthesis, transpiration and partitioning of biomass from vegetative parts to economic parts (e.g. Akhter et al., 2009). However, morphological and physiological adaptations tend to take place in response to variation in solar radiation in order to maintain maximum photosynthetic efficiency of the leaves (Duriyaprapan and Britten, 1982). A number of studies have shown that any kind of shading reduces productivity (Copeland, 1911; Strover, 1984; Israeli et al., 1994; Stanhill and Cohen, 2001; Akhter et al., 2009), while others have found that crop productivity increases under moderate shade (Boardman, 1977; Björkman and Holmgren, 1966; Holmgren, 1968; Batugal, 1977; Raveh et al., 2003; Isaac et al., 2007; Saifuddin et al., 2010).

The information available on the effects of insolation and water availability on abaca growth and development is scarce, although much has been published on responses to fertilizer application and on how these parameters affect biomass production and yield under field conditions where biophysical factors are very variable. To date, there are only two scientific and published reports available involving studies of abaca growth under different shade levels with conflicting results. The pioneering study of Copeland (1911) found out that growth rate and dry weight of abaca plants grown under shade were lower than those of abaca grown without shade. In contrary, Batugal et al. (1977) documented that improved growth and yield (variety *Tinawagang puti*) was observed under partial shading at 33% and 66% than in open space. Therefore, in this study, the emphasis was on the investigation of the effect of reducing irradiance by 30%, 40% and 50% of full sunlight using polypropylene shade nets on abaca's morphological and physiological performance. Likewise, the study aimed to find out if irrigation and fertilizer application could offset the effect of shade on the ecophysiological performance of abaca. Finally, to identify possible interaction effects of shade and irrigation-fertilization on abaca's morphological and physiological parameters measured.

2.2 Materials and methods

2.2.1 Biophysical and climatic condition of the study site

The study site was established in an abaca farmer's area in Barangay Catmon, Ormoc City, Philippines. The site is located at 11^{o} 04′ 52.4″ N and 124^{o} 34′ 29.5″ E on an alluvial terrace, 44.5 meters above mean sea level and on a slope of 0-3%. Average annual precipitation is 2600mm yr^{-1} and mean annual temperature is 27.5 ^{o}C. The area was previously planted to sugarcane (*Saccharum officinarum*) and was then left fallow for ten years. Constant grazing caused the grasses to dominate the vegetation structure of the site. The soil is classified as Alisol, whose clay fraction is dominated by kaolinite and haloysite. The soil contains significant amounts of goethite and hematite with more than 60% P retention capacity.

The results of the soil profile examination revealed that both soil profiles were characterized by Ap-Bw-Bt_1-Bt_2 horizon sequence to a depth of one meter. This indicates an accumulation of silicate clay that has formed in the horizon or has moved into it by illuviation or either both. Soil textures ranged from clay loam on the surface to silty clay loam in the subsoil. The soil structure was strong to moderate coarse granular structure in the A horizon and strong to moderate sub-angular blocky structure in the lower horizon. Such structure is common in tropical soils which are well developed and which have high clay content (Asio, 1996). Ants, millipedes and centipedes were observed in the surface horizon and earthworms, adult and larvae termites were noted in the subsurface horizon of both profiles during the examination. High intensity rooting development occurred in the upper 0-20 cm soil depth of both profiles evaluated. Bulk density measurements showed low values indicating a porous soil (Table 2.1). The data revealed that the soil was deep, porous, with a good soil structure and an excellent drainage. Armecin and Gabon (2008) and Sievert (2009), consider these as the soil morphological characteristics favourable for abaca production.

Table 2.1 Mean values of selected soil properties for the 0-30 cm and 30-60 cm soil depths

Soil Properties	Soil Depth (cm)	
	0-30	30-60
pH (KCl)	5.16±0.39	5.14±0.04
Organic matter (%)	2.83±0.23	1.32±0.03
Total N (g kg^{-1})	1.53±0.03	1.05±0.04
Available P (mg kg^{-1})	30.67±2.72	4.17±0.97
Exchangeable K ($cmol_c$ kg^{-1})	0.52±0.04	0.55±0.04
Bulk density (g cm^{-3})	1.11±0.00	1.06±0.01

***Note*:** n=16

The average values of selected soil chemical properties of the study site are presented in Table 1. As can be seen, the pH values for the 0-30 cm and 30-60 cm soil depths were 5.23 and 5.14, respectively. These pH values indicate strongly acidic conditions (Soil Conservation Society of America, 1982). Bulk density ranged from 1.05 g cm^{-3} to 1.12 g cm^{-3} with very minor variations in the values indicating high porosity of the soil. Furthermore, results revealed that there were no significant differences in the total nitrogen between different treatments and soil depths. Available phosphorus was much higher in the top soil (0-30 cm) than in the sub-surface (30-60 cm).

2.2.2 Propagation of planting materials at the nursery

Potting media (i.e., top soil, rice hull ash and compost) were mixed at 2:1:1 kg ratio and sterilized at 105 °C for 4 hours. After 24 hours, the sterilized media were bagged in 10cm x 15cm polyethylene bags at the green house. At the same time, tissue cultured plantlets were acclimatized at the laboratory for a week in preparation for potting. During potting, plantlets were taken out from the bottle container and washed with sterilized water to remove the agar gel from the roots. Immediately, the plantlets were soaked in water treated with fungicide for two minutes. Yellow leaves were removed while each plantlet was separated from the clump. The plantlet was individually potted in soil-filled polyethylene bags and placed in a sealed recovery chamber for one month until new leaves (at most 3) developed.

After one month, the recovery chamber was opened in segment (1 division per week) to acclimatize the seedlings to outside climatic conditions. Watering was done in an every-other-day interval. No fertilizer (either organic or inorganic) was applied to guarantee uniform nutritional status of the planting material prior to out-planting. Due to the rapid growth of the seedlings, re-bagging was done (using 15cm x 25cm polyethylene bags) two months from potting to allow more space for root development.

Three months after potting, the planting materials were hauled to the temporary nursery constructed at the middle of the study site to acclimatize the seedlings from on-site climatic condition prior to out-planting. This process was done for another three months where watering was minimized and light infiltration was increased (by removing slightly the shade materials) every week. During this period, the seedlings were evaluated and classified according to height, girth and number of leaves. The result was the basis in selecting and distributing the seedlings per treatment to guarantee uniform morphological characteristics of planting material per plot to reduce bias between plants.

2.2.3 Experimental design and installation of shade nets

The design of the experiment was a 4x4 factorial combination of shade and irrigation-fertilizer application. Tissue-cultured abaca seedlings (var. *Laylay*) were planted in a split-plot randomized block design with four replications. The dimension of each main plot (shade) was 30m x 30m. Since there were four sub-plots (i.e., irrigation and fertilizer application), a total of 64 plots were established with a dimension of 12.5m x12.5m $plot^{-1}$. The planting distance used was 2.5m x 2.5m (square method) that corresponded to a total of 36 abaca seedlings $plot^{-1}$.

Three different shade nets made of polypropylene (Bayview Fishing Supply and General Merchandise, Manila, Philippines) were used: B-double (4mm x 5mm mesh size), A-double (3.5mm x 2.5mm mesh size) and dry nets (2mm x 2mm mesh size) that permitted 70%, 60%, and 50% of full sunlight, respectively. The nets were installed at an initial height of 3.66 meters and were heightened to six meters seven months after planting. Photosynthetically active radiation (PAR) was measured at weekly intervals in all levels of shading using a LI-COR 190 SA quantum sensor.

2.2.4 Irrigation, fertilizer application and crop management

A drip irrigation system was improvised by installing 288 20-liter water containers in sub-sub-plots. One container was installed at the center of four abaca plants. Containers were placed using compass and leveling equipment to attain uniform distribution of water among plants at a rate of 5 liters per plant per application. Since there was no available information on the evaporative demand of the crop in the field, irrigation was applied when soil moisture 26% and was determined using the gravimetric method. The frequency of irrigation was applied two times at seedling stage (1-3 MAP), three times at the early vegetative stage (4-6 MAP), four times at the late vegetative stage (7-9 MAP), and five times at flagleaf stage (10-12 MAP). The reason of increasing the frequency of watering was due to an increase of emergence of additional suckers.

A blanket application of 14 grams N (ammonium nitrate), P_2O_5 (phosphoric acid), K_2O (potassium oxide) per plant was made for each of the fertilized plots using complete (14-14-14) fertilizer applied at the base of the plant during planting. Then, placement application using the same rate and fertilizer was done three and six months after planting adopting the National Abaca Research Center's (NARC) recommendation. The rate was increased to 40 grams plant^{-1} at nine and twelve months after planting following the recommendation of the Fiber Development Authority (FIDA).

Monthly hand weeding was conducted when the surrounding vegetation of the plantation threatened to interfere with the growth of the abaca plants. Suckers were pruned bimonthly to control overproduction which could eventually affect the physiological performance of the mother (sample) plant.

2.2.5 Destructive harvesting and determination of dry biomass

Destructive harvesting was conducted at three (seedling stage), six (early vegetative stage), nine (late vegetative stage) and twelve (flagleaf stage) months after planting. Four sample plants (excluding border plants) per treatment per replication were excavated (64 plants per sampling) constituting 256 plants harvested in the entire duration of the experiment. Plant height, pseudostem length and girth were measured in every harvest. Leaf width and length were measured and leaf area was calculated using the formula length x width x 0.83 (Summerville, 1944; Israeli et al., 1994; Armecin and Gabon, 2008). Biomass samples were partitioned into plant organs (i.e., roots, corm, leaf sheath or pseudo stem, leaf stalks, leaves and suckers). For each plant fraction, fresh and dry weight (after oven drying at 105 °C for 24 hours resp. until a constant weight was reached) were determined. Leaf area ratios (LAR) and net assimilation rate (NAR) were calculated using the following equations (Lambers et al., 1998 and Caliskan et al., 2009).

$$LAR\ (\mathrm{m^{2}\,kg^{-1}}) = \frac{\mathrm{LA}}{\mathrm{L_{DM}}} \qquad (1)$$

$$NAR\ (\mathrm{g\,m^{-2}\,d^{-1}}) = \left[\frac{1}{\mathrm{LA}}\right]\frac{\mathrm{dW}}{\mathrm{dt}} \qquad (2)$$

Where: LA = leaf area (m^2)
L_{DM} = Leaf dry matter (kg)
W = Total plant dry weight (g)
t = Time (d)

2.2.6 Statistical analyses

All data were tested for normality and homogeneity using PROC Univariate of Statistical Analysis System version 9.1 (SAS, 2003). PROC GLM (General linear model) procedure was initially performed to assess the significant effects of shading, irrigation, fertilizer application and their interactions on abaca's morphological and physiological characteristics using the complete model as follows:

$$y_{ijkl} = \mu + H_i + S_j + IF_k + (H*S)_{ij} + (S*IF)_{jk} + (H*IF)_{ik} + e_{ijkl}$$

Where: y_{ijkl} = parameter of interest (y = plant height (cm), pseudostem length (cm), pseudostem girth (cm), cumulative leaf area (cm^2), number of leaves, number of suckers, effective rooting zone (cm^2), dry biomass of different plant organs (g), aboveground dry biomass (g), belowground dry biomass (g), total dry biomass (g), leaf area ratio (m^2 kg^{-1}), net assimilation rate (g m^{-2} d^{-1}), stem weight ratio (%) and leaf weight ratio (%)

μ = overall mean for the parameter of interest

H_i = effect of the i^{th} stages of plant growth (i = 1 to 4) where 1= seedling, 2 = early vegetative, 3 = late vegetative, 4 = flagleaf

S_j = effect of the j^{th} shading treatments (j = 1 to 4) where 1 = 0% shade (control), 2 = 30% light, 3 = 40% light infiltration, 4 = 50% light infiltration

IF_k = effect of the k^{th} irrigation and fertilizer application (k = 1 to 4) where 1 = without irrigation and fertilization (control), 2 = without irrigation, with fertilization, 3 = with irrigation, without ferlization, 4 = with irrigation and fertilization

$(H*S)_{ij}$ = interaction effect of the i^{th} stages of plant growth and j^{th} shading treatments

$(S*IF)_{jk}$ = interaction effect of the j^{th} shading treatments and k^{th} irrigation and fertilizer application

$(H*IF)_{ik}$ = interaction effect of the i^{th} stages of plant growth and k^{th} irrigation and fertilizer application

e_{ijkl} = random error associated with each record

The final models for each response variable were analyzed but including only those significant main factor and two factor interaction effects for each stage of growth data set. Duncan multiple range test (DMRT) and least squares differences (LSD) were carried out to compare treatment means of independent variables with significant variations at probability<0.05.

2.3 Results

2.3.1 Morphological response to shade

Plant height, pseudostem length and girth, cumulative leaf area, number of leaves, effective rooting depth and number of suckers were significantly ($p \leq 0.01$) affected when light irradiance was further reduced to 50% shade. Duncan multiple range test (DMRT) and least squares differences revealed that shade consistently and positively affected these parameters from seedling stage until flagleaf stage (Table 2.2). The highest growth rate on plant height, pseudostem length and girth was documented at the late vegetative stage and flagleaf stage.

Furthermore, shade significantly decreased ($p \leq 0.05$) the suckering ability of the plant during its seedling and flagleaf stages. The accelerated production of suckers or followers per unit of time is important in replenishing harvested stalks which is a desirable character of abaca. It was recorded that suckers (average of three) started to emerge two weeks after planting. However, these were pruned until the mother plant reached early vegetative stage to avoid exhaustive below ground competition. During the flagleaf stage (final harvest), an average of 12 suckers per plant was recorded.

Table 2.2 Morphological parameters of abaca at different stages of growth as affected by shade across irrigation and fertilizer application treatments

Parameters	Shading Treatments	Stages of Plant Growth			
		Seedling	Early vegetative	Late vegetative	Flagleaf
Plant Height (cm)	0% shade	112.19 ± 7.73^{c}	149.95 ± 12.39^{c}	237.25 ± 18.26^{b}	299.75 ± 17.22^{c}
	30% shade	155.69 ± 7.73^{b}	219.75 ± 12.39^{ab}	285.78 ± 18.26^{b}	335.51 ± 17.22^{bc}
	40% shade	158.18 ± 7.73^{b}	213.28 ± 12.39^{b}	289.53 ± 18.26^{b}	367.28 ± 17.22^{b}
	50% shade	186.96 ± 7.73^{a}	254.06 ± 12.39^{a}	362.76 ± 18.26^{a}	417.93 ± 17.22^{a}
Pseudostem length (cm)	0% shade	47.42 ± 3.69^{b}	65.58 ± 5.64^{c}	112.26 ± 9.29^{c}	142.63 ± 10.26^{c}
	30% shade	70.41 ± 3.69^{a}	97.94 ± 5.64^{b}	133.50 ± 9.29^{bc}	176.22 ± 10.26^{b}
	40% shade	69.35 ± 3.69^{a}	97.20 ± 5.64^{b}	147.00 ± 9.29^{ab}	179.63 ± 10.26^{b}
	50% shade	79.09 ± 3.69^{a}	118.25 ± 5.64^{a}	171.03 ± 9.29^{a}	228.50 ± 10.26^{a}
Pseudostem base girth (cm)	0% shade	6.28 ± 0.31^{b}	7.29 ± 0.46^{b}	11.11 ± 0.53^{c}	13.18 ± 0.50^{b}
	30% shade	8.12 ± 0.31^{a}	10.21 ± 0.46^{a}	12.47 ± 0.53^{bc}	13.51 ± 0.50^{b}
	40% shade	7.40 ± 0.31^{a}	10.42 ± 0.46^{a}	12.91 ± 0.53^{ab}	15.54 ± 0.50^{a}
	50% shade	8.08 ± 0.31^{a}	11.32 ± 0.46^{a}	14.16 ± 0.53^{a}	16.10 ± 0.50^{a}
Cumulative leaf area (cm^2)	0% shade	6721.96 ± 1390.58^{b}	10669.14 ± 2728.84^{b}	29979.33 ± 5702.99^{b}	26663.92 ± 4207.09^{c}
	30% shade	11601.16 ± 1390.58^{a}	23139.17 ± 2728.84^{a}	35213.77 ± 5702.99^{b}	27463.23 ± 4207.09^{c}
	40% shade	11279.50 ± 1390.58^{a}	24237.62 ± 2728.84^{a}	43446.11 ± 5702.99^{ab}	46918.37 ± 4207.09^{b}
	50% shade	14807.96 ± 1390.58^{a}	28087.46 ± 2728.84^{a}	59049.64 ± 5702.99^{a}	59735.92 ± 4207.09^{a}
Number of leaves	0% shade	7.25 ± 0.37^{a}	7.56 ± 0.40^{b}	9.81 ± 0.54^{a}	6.38 ± 0.37^{c}
	30% shade	8.31 ± 0.37^{a}	9.38 ± 0.40^{a}	10.81 ± 0.54^{a}	6.81 ± 0.37^{c}
	40% shade	8.17 ± 0.37^{a}	9.31 ± 0.40^{a}	10.94 ± 0.54^{a}	8.25 ± 0.37^{b}
	50% shade	8.69 ± 0.37^{a}	9.81 ± 0.40^{a}	11.69 ± 0.54^{a}	9.81 ± 0.37^{a}
Effective rooting depth (cm)	0% shade	35.69 ± 2.14^{a}	34.56 ± 3.34^{b}	49.50 ± 5.67^{a}	51.75 ± 5.55^{c}
	30% shade	31.00 ± 2.14^{a}	46.50 ± 3.34^{a}	56.00 ± 5.67^{a}	57.75 ± 5.55^{bc}
	40% shade	34.19 ± 2.14^{a}	52.88 ± 3.34^{a}	51.81 ± 5.67^{a}	79.25 ± 5.55^{a}
	50% shade	34.31 ± 2.14^{a}	45.19 ± 3.34^{a}	63.44 ± 5.67^{a}	70.00 ± 5.55^{ab}
Number of suckers	0% shade	9.94 ± 0.74^{b}	12.19 ± 0.95^{a}	14.81 ± 0.84^{a}	11.81 ± 0.74^{ab}
	30% shade	13.31 ± 0.74^{a}	13.50 ± 0.95^{a}	13.94 ± 0.84^{a}	13.94 ± 0.74^{a}
	40% shade	11.75 ± 0.74^{ab}	13.75 ± 0.95^{a}	13.38 ± 0.84^{a}	12.56 ± 0.74^{ab}
	50% shade	12.44 ± 0.74^{a}	15.25 ± 0.95^{a}	12.44 ± 0.84^{a}	10.88 ± 0.74^{a}

***Note*:** Least squares means in each column within the cell with different letter superscripts (a-c) are significantly different at $p<0.05$, n = 16

2.3.2 Physiological response to shade

The influence of shade on abaca's physiological characteristics, i.e., dry matter production, leaf area ratio and net assimilation rate were significant not only during flagleaf stage, but throughout the different stages of plant growth. Furthermore, GLM procedure showed that shade constantly increased pseudostem dry matter (DM), root DM, leaf DM, corm DM, leafstalks DM, aboveground DM, belowground DM, and total plant DM.

Figure 2.1 shows that the abaca planted in 50% shade significantly increased ($p \leq 0.01$) growth rate ($g_{dry\ matter}$ d^{-1}) compared to 0% shade (full sunlight).The results of the GLM procedure showed that shade ($p \leq 0.01$) positively affected crop growth rate from seedling stage to flagleaf stage. It is also worth mentioning that the lowest crop growth rate (CGR) was documented at seedling stage while the highest was recorded at late vegetative stage and started to decline at flagleaf stage (Table 2.3). This shows that abaca plants were deeply affected by high radiation (temperature) causing photoinhibition and/or photooxidative damage at seedling stage and early leaf senescence at flagleaf stage.

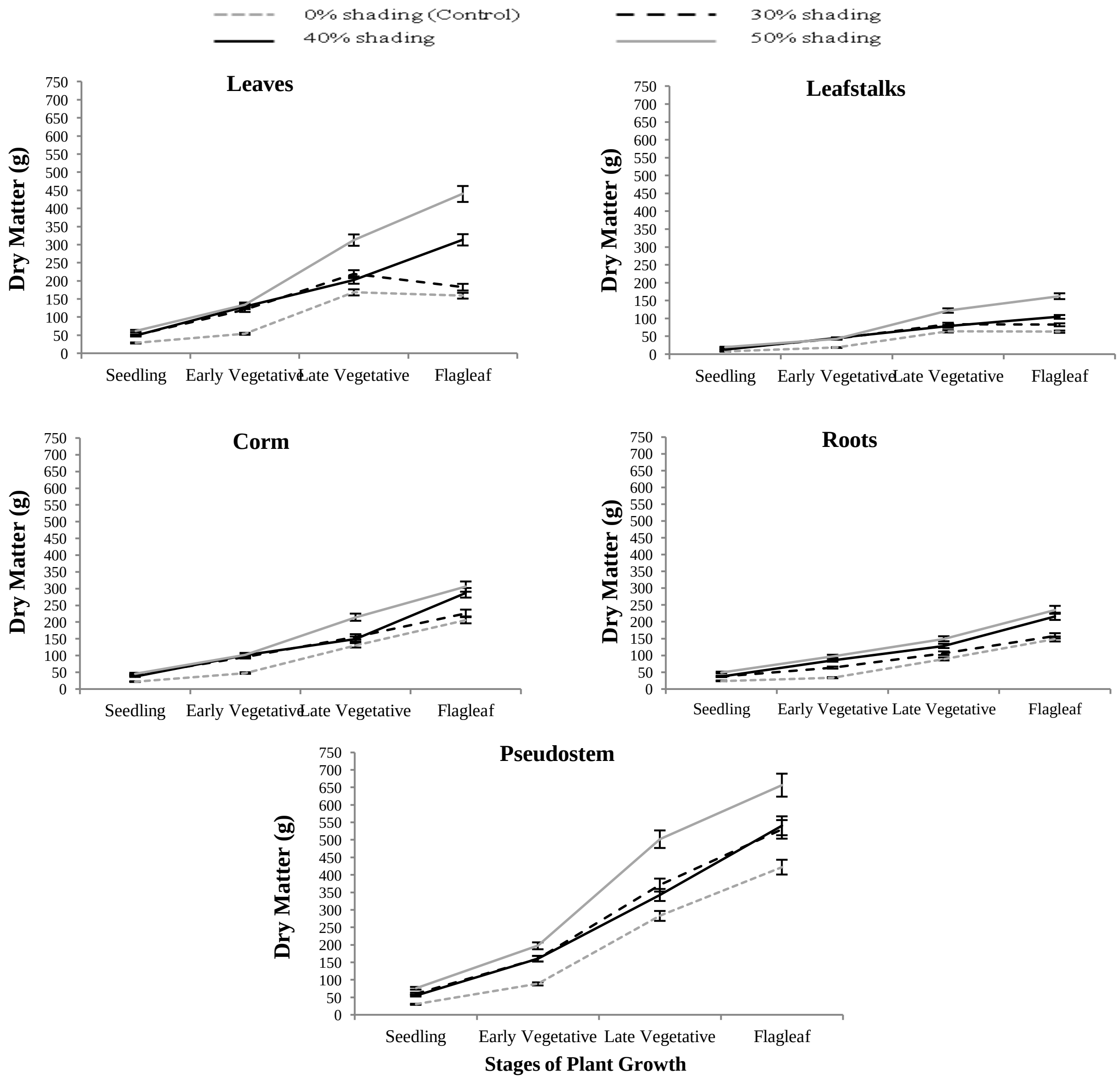

Fig. 2.1 Dry matter production among abaca plant organs at different stages of growth as affected by shade across irrigation and fertilizer application treatments

The results on net assimilation rate (NAR) computation (Table 2.3) strongly substantiated the results presented in Figure 2.2 where reduced irradiance constantly and positively affected dry matter production among plant organs from seedling to flagleaf growth stage. Analysis of variance showed that shade significantly enhanced NAR at seedling stage ($p \leq 0.01$) and late vegetative stage ($p \leq 0.05$).The low crop growth rate documented on sample plants grown in 0% shade during seedling stage was due to negative effect of radiation on leaves of abaca plants (photooxidative damage) leading to low net assimilation rate (photoinhibition). This clearly proves that abaca is a shade tolerant plant that could withstand low light availability and is physiologically efficient in converting radiation to dry matter over a broad range of resource availabilities.

At late vegetative stage, the plants grown in 0% shade were able to recuperate and improve their net assimilation rate but physiological recovery was not enough in order to exceed or even equal the productivity of abaca grown in the 50% shade. This was because the plants were nearly approaching their maturity, switching from vegetative to generative phase of crop growth.

Table 2.3 Crop growth rate, leaf area ratio and net assimilation rate at different stages of growth as affected by shade across irrigation and fertilizer application treatments

Growth Parameters	Shading Treatments	Stages of Plant Growth			
		Seedling	Early vegetative	Late vegetative	Flagleaf
Crop Growth Rate ($g\ d^{-1}$)	0% shade	0.45 ± 0.19^{b}	1.29 ± 0.40^{a}	3.94 ± 0.82^{a}	1.88 ± 0.62^{b}
	30% shade	1.14 ± 0.19^{a}	2.22 ± 0.40^{a}	3.88 ± 0.82^{a}	1.84 ± 0.62^{b}
	40% shade	1.07 ± 0.19^{a}	2.41 ± 0.40^{a}	3.21 ± 0.82^{a}	3.73 ± 0.62^{a}
	50% shade	1.52 ± 0.19^{a}	2.41 ± 0.40^{a}	6.25 ± 0.82^{a}	3.58 ± 0.62^{a}
Leaf Area Ratio ($m^2\ kg^{-1}$)	0% shade	10.28 ± 0.51^{a}	7.86 ± 0.38^{a}	6.79 ± 0.32^{a}	4.30 ± 0.27^{ab}
	30% shade	9.78 ± 0.51^{a}	7.42 ± 0.38^{a}	5.58 ± 0.32^{b}	3.80 ± 0.27^{b}
	40% shade	9.98 ± 0.51^{a}	7.49 ± 0.38^{a}	7.12 ± 0.32^{a}	4.91 ± 0.27^{a}
	50% shade	10.00 ± 0.51^{a}	7.66 ± 0.38^{a}	6.48 ± 0.32^{ab}	4.90 ± 0.27^{a}
Net Assimilation Rate ($g\ m^{-2}\ d^{-1}$)	0% shade	0.53 ± 0.08^{b}	0.70 ± 0.14^{a}	1.15 ± 0.10^{a}	0.69 ± 0.15^{a}
	30% shade	0.90 ± 0.08^{a}	0.81 ± 0.14^{a}	0.96 ± 0.10^{ab}	0.63 ± 0.15^{a}
	40% shade	0.89 ± 0.08^{a}	1.05 ± 0.14^{a}	0.71 ± 0.10^{b}	0.80 ± 0.15^{a}
	50% shade	0.95 ± 0.08^{a}	0.82 ± 0.14^{a}	0.97 ± 0.10^{ab}	0.66 ± 0.15^{a}

***Note*:** Least squares means in each column within the cell with different letter superscripts (a-b) are significantly different at $p<0.05$, n = 16

2.3.3 Morphological response to irrigation and fertilizer application

The effect of fertilizer application on the morphological parameters measured became evident shortly after out-planting until harvest (Table 2.4). This considerably increased ($p \leq 0.05$) plant height, cumulative leaf area, pseudostem length and base girth. However, there was no significant effect of supplemental irrigation on the growth parameters measured.

2.3.4 Physiological response to irrigation and fertilizer application

Figure 2.2 shows that the abaca plants treated with NPK fertilizer have consistently accumulated higher biomass in all of the partitioned plant organs from seedling stage to flagleaf stage. In contrast, supplemental irrigation has no significant effect on the physiological parameters measured. This implies that the incident rainfall during the period of the experiment was sufficient for plant growth and development. However, the result could be different during long drought periods caused by El Niño or climate change.

Furthermore, crop growth rate was consistently and positively affected ($p \leq 0.05$) by NPK fertilizer application across shading treatments (Table 2.5). The leaf area ratio computation revealed that abaca was significantly affected by fertilizer application during the early and late vegetative stages.

Likewise, results indicated that lesser amounts of biomass were partitioned to the leaves and more allocated to the pseudostem during the abovementioned developmental stages. This corroborated the findings presented in Table 2.4 wherein highest growth rate on the plant's pseudostem length and base girth was documented at late vegetative stage.

Table 2.4 Morphological parameters of abaca measured at different stages of plant growth as affected by irrigation (I) and fertilizer (F) application across shade treatments

Parameters	Irrigation and Fertilizer Treatments	Stages of Plant Growth			
		Seedling	Early vegetative	Late vegetative	Flagleaf
Plant Height (cm)	Without I and F	133.05 ± 7.73^{b}	173.84 ± 12.39^{b}	240.59 ± 18.26^{b}	329.27 ± 17.22^{a}
	Without I, with F	158.81 ± 7.73^{a}	236.13 ± 12.39^{a}	322.94 ± 18.26^{ab}	376.84 ± 17.22^{a}
	With I, without F	150.15 ± 7.73^{ab}	192.76 ± 12.39^{b}	278.35 ± 18.26^{bc}	331.49 ± 17.22^{a}
	With I and F	170.99 ± 7.73^{a}	234.31 ± 12.39^{a}	333.44 ± 18.26^{a}	382.88 ± 17.22^{a}
Pseudostem length (cm)	Without I and F	59.03 ± 3.69^{a}	79.28 ± 5.64^{c}	112.88 ± 9.29^{b}	163.93 ± 10.26^{b}
	Without I, with F	69.75 ± 3.69^{a}	103.09 ± 5.64^{ab}	160.64 ± 9.29^{a}	198.29 ± 10.26^{a}
	With I, without F	65.03 ± 3.69^{a}	88.63 ± 5.64^{bc}	131.51 ± 9.29^{b}	163.00 ± 10.26^{b}
	With I and F	72.33 ± 3.69^{a}	107.96 ± 5.64^{a}	158.75 ± 9.29^{a}	201.75 ± 10.26^{a}
Pseudostem base girth (cm)	Without I and F	6.60 ± 0.31^{b}	8.38 ± 0.46^{b}	10.88 ± 0.53^{b}	13.29 ± 0.50^{b}
	Without I, with F	8.02 ± 0.31^{a}	11.09 ± 0.46^{a}	13.94 ± 0.53^{a}	15.21 ± 0.50^{a}
	With I, without F	7.20 ± 0.31^{ab}	8.98 ± 0.46^{b}	12.01 ± 0.53^{b}	14.23 ± 0.50^{ab}
	With I and F	8.05 ± 0.31^{a}	10.79 ± 0.46^{a}	13.83 ± 0.53^{a}	15.59 ± 0.50^{a}
Cumulative leaf area (cm^{2})	Without I and F	8371.09 ± 1390.58^{b}	17617.60 ± 2728.84^{bc}	29752.40 ± 5702.99^{b}	35320.99 ± 4207.09^{a}
	Without I, with F	12052.31 ± 1390.58^{ab}	24692.11 ± 2728.84^{ab}	56150.28 ± 5702.99^{a}	44182.29 ± 4207.09^{a}
	With I, without F	10054.69 ± 1390.58^{ab}	16495.30 ± 2728.84^{c}	40165.85 ± 5702.99^{ab}	36797.68 ± 4207.09^{a}
	With I and F	13932.48 ± 1390.58^{a}	27328.38 ± 2728.84^{a}	41620.31 ± 5702.99^{ab}	44480.46 ± 4207.09^{a}
Number of leaves	Without I and F	7.63 ± 0.37^{a}	8.50 ± 0.40^{b}	9.75 ± 0.54^{a}	7.50 ± 0.37^{a}
	Without I, with F	8.38 ± 0.37^{a}	9.18 ± 0.40^{ab}	11.50 ± 0.54^{a}	7.94 ± 0.37^{a}
	With I, without F	7.63 ± 0.37^{a}	8.31 ± 0.40^{b}	10.44 ± 0.54^{a}	7.44 ± 0.37^{a}
	With I and F	8.75 ± 0.37^{a}	10.06 ± 0.40^{a}	11.56 ± 0.54^{a}	8.38 ± 0.37^{a}
Number of suckers	Without I and F	11.06 ± 0.74^{a}	12.25 ± 0.95^{b}	13.13 ± 0.84^{a}	11.25 ± 0.74^{a}
	Without I, with F	12.00 ± 0.74^{a}	15.00 ± 0.95^{a}	14.38 ± 0.84^{a}	12.25 ± 0.74^{a}
	With I, without F	12.19 ± 0.74^{a}	12.13 ± 0.95^{b}	13.69 ± 0.84^{a}	13.81 ± 0.74^{a}
	With I and F	12.19 ± 0.74^{a}	15.31 ± 0.95^{a}	13.38 ± 0.84^{a}	11.88 ± 0.74^{a}

***Note*:** Least squares means in each column within the cell with different letter superscripts (a-c) are significantly different at $p<0.05$, n = 16

Table 2.5 Crop growth rate, leaf area ratio and net assimilation rate of abaca at different stages of growth as affected by irrigation (I) and fertilizer (F) application across shade treatments

Growth Parameters	Irrigation and Fertilizer Treatments	Stages of Plant Growth			
		Seedling	Early vegetative	Late vegetative	Flagleaf
Crop Growth Rate (g d^{-1})	Without I and F	0.67 ± 0.19^{b}	1.36 ± 0.40^{b}	2.28 ± 0.82^{b}	1.88 ± 0.62^{a}
	Without I, with F	1.24 ± 0.19^{a}	2.67 ± 0.40^{a}	6.18 ± 0.82^{a}	1.84 ± 0.62^{a}
	With I, without F	0.89 ± 0.19^{ab}	1.47 ± 0.40^{b}	3.97 ± 0.82^{ab}	3.73 ± 0.62^{a}
	With I and F	1.37 ± 0.19^{a}	2.82 ± 0.40^{a}	4.84 ± 0.82^{a}	3.58 ± 0.62^{a}
Leaf Area Ratio (m^{2} kg^{-1})	Without I and F	10.49 ± 0.51^{a}	8.81 ± 0.38^{a}	7.43 ± 0.32^{a}	4.90 ± 0.27^{a}
	Without I, with F	9.34 ± 0.51^{a}	6.69 ± 0.38^{b}	6.31 ± 0.32^{b}	4.40 ± 0.27^{a}
	With I, without F	10.22 ± 0.51^{a}	7.52 ± 0.38^{b}	6.95 ± 0.32^{ab}	4.62 ± 0.27^{a}
	With I and F	10.00 ± 0.51^{a}	7.41 ± 0.38^{b}	5.28 ± 0.32^{c}	4.00 ± 0.27^{a}
Net Assimilation Rate (g m^{-2} d^{-1})	Without I and F	0.65 ± 0.08^{b}	0.58 ± 0.14^{a}	0.74 ± 0.10^{a}	0.76 ± 0.15^{a}
	Without I, with F	0.95 ± 0.08^{a}	0.95 ± 0.14^{a}	1.01 ± 0.10^{a}	0.37 ± 0.15^{a}
	With I, without F	0.77 ± 0.08^{ab}	0.77 ± 0.14^{a}	0.90 ± 0.10^{a}	0.84 ± 0.15^{a}
	With I and F	0.90 ± 0.08^{a}	1.09 ± 0.14^{a}	1.12 ± 0.10^{a}	0.80 ± 0.15^{a}

***Note*:** Least squares means in each column within the cell with different letter superscripts (a-c) are significantly different at $p<0.05$, n = 16

Statistical analysis revealed NPK fertilization significantly improved NAR at seedling stage. This shows that adequate nutrient supply (i.e., NPK) is very critical during the early developmental stage of the crop. However, the application of fertilizer on the succeeding stages of plant growth led to higher biomass production but its effect was generally insignificant.

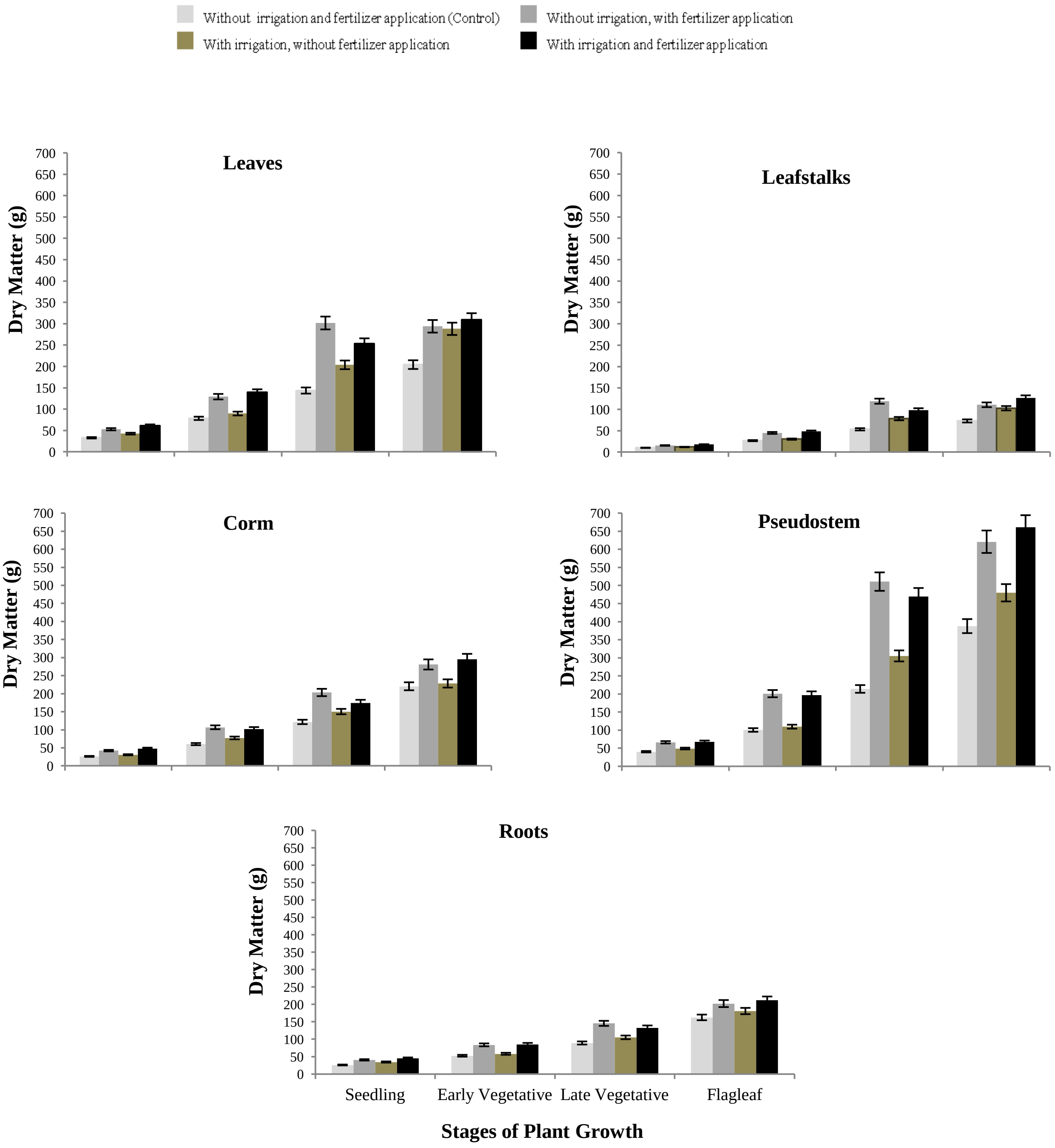

Fig. 2.2 Dry matter production among abaca plant organs at different stages of growth as affected by irrigation and fertilizer application across shade treatments

2.3.5 Interaction effects

Analysis of variance revealed that there was a two-factor interaction effect of shade and combination of irrigation and fertilizer application treatments on LAR at early vegetative stage (probability=0.0164) and flagleaf stage (probability=0.0094). This two-factor interaction (Figures 2.3 and 2.4) is substantiated by the findings presented in Table 2.2 where both cumulative leaf area and number of leaves was significantly affected by shade at early vegetative stage and flagleaf stage. Furthermore, the combination of irrigation and fertilizer application considerably increased the cumulative leaf area and number of leaves at early vegetative stage (Table 2.4).

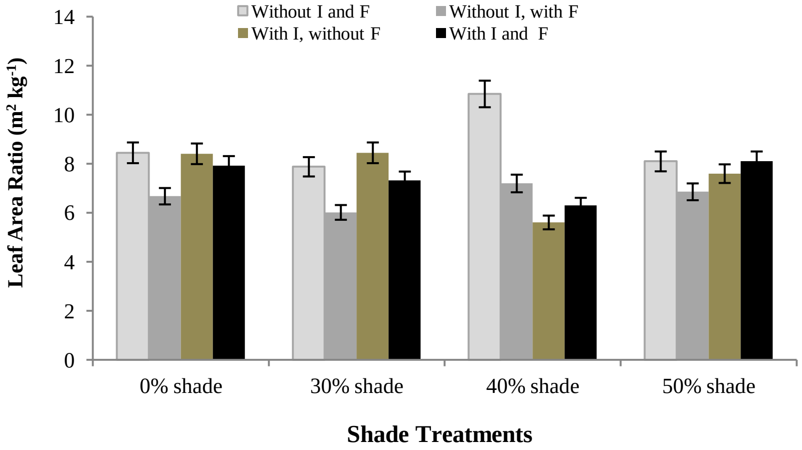

Fig. 2.3 Two-factor interaction effects of shade and irrigation-fertilization on the leaf area ratio of abaca at early vegetative stage

The interaction effect of shade and irrigation-fertilization on the leaf area ratio at flagleaf stage could be attributed to the differential leaf senescence in the different treatments. In this stage the plants were indeed approaching maturity where the leaf dry matter had begun to decrease.

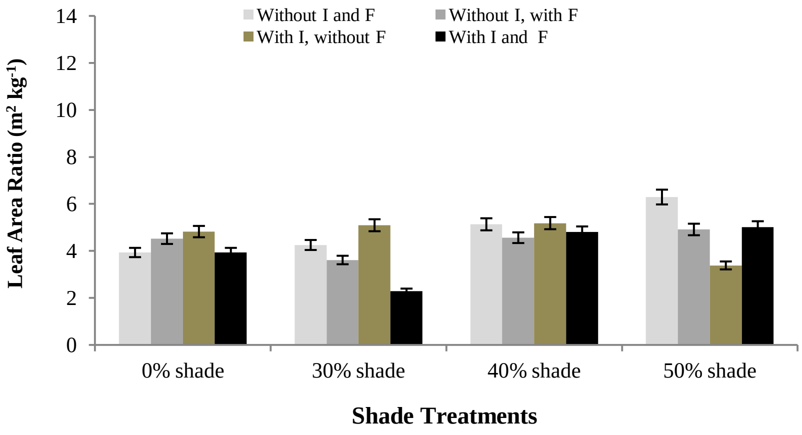

Fig. 2.4 Two factor interaction effects of shade and irrigation-fertilization on leaf area ratio of abaca at flagleaf stage

2.4 Discussion

The significant effect on abaca morphology (e.g., improved growth) and physiology (e.g., high CGR, LAR and NAR) planted in 50% shade was found in this study. The stronger effect was on plant height, pseudostem length and base girth, biomass production and yield on abaca planted in 50% shade compared to plants grown in 0% shade (full sunlight). This is consistent with the findings of Batugal et al. (1977) on abaca (*tinawagang puti* variety) where improved growth and yield under 66% light infiltration was recorded. Torquebiau and Akeampong (1994) and Senevirathna et al. (2008) studying edible bananas (*Musa x paradisiaca*) under different irradiance documented highest biomass and yield at 50% light. While, Söndahl et al. (2005) recommended that overhead shade in arabica coffee (*Coffea arabica*) should not reduce more than 50% of total irradiances to attain an optimum yield. Van der Vossen (1985) explained that arabica coffee is typically a shade-adapted species (like abaca) and becomes severely stressed when grown without overhead shade and has lower yields. On the other hand, increased stem height and size in response to shade has been reported in *arabica* coffee (Van der Vossen, 2005), *Theobroma cacao* (Isaac et al., 2007), *Citrus reticulata* x *sinensis* (Raveh et al, 2003) and *Bougainvillea glabra* (Saifuddin et al., 2010). In contrary, reduced growth and stem diameter have been recorded in *Carica papaya* (Buisson and Lee, 1993) and *Musa acuminata* Grand Nain cultivar (Israeli et al., 1995) plants grown under shade.

The net assimilation rate (NAR) calculations clearly showed that the sample plants were constantly and positively affected by shade ($p \leq 0.01$) and NPK fertilization ($p \leq 0.05$) at seedling stage until flagleaf stage. However, NAR values were very low even on abaca plants grown in full sunlight. Valladares and Niinemets (2008) reported that shade-adapted species usually have low net photosynthesis rates and are very sensitive to photoinhibition. Abaca is known to be an understorey plant species of the Philippines' tropical lowland evergreen rainforests and is a typically shade-adapted species (Tabora Jr., 1978; Halos, 2008; Sievert; 2009). Furthermore, the abaca planted in full sunlight (0% shade) had lower NAR compared to plants grown in shaded treatments at seedlings stage (Table 2.3). This corroborated the results on the morphological performance presented in Table 2.2. The data on field documentation also revealed that the leaves of abaca planted in 0% shade (two months after planting – seedling stage) got sunburned (photooxidative damage) due to high radiation (temperature) even though the planting materials were properly acclimatized for a period of three months prior to field planting (see SP1 of Supplementary Information). Osmond (1994) and Goltsev et al. (2003) reported that high radiation can destroy photosynthetic pigments or can lead to chloroplast damage and chlorophyll bleaching (Björman, 1981; Powles, 1984) therefore inhibits photosynthesis resulting in lower assimilation yield (Lambers et al., 1998; Saifuddin et al., 2010). The study of Kamaluddin and Grace (1991) on the effect of photoinbition and light acclimation in *Bischofia javanica* seedlings revealed that shade leaves when exposed to high light exhibited a depression in the chlorophyll fluorescence ratio with concomitant decline in pool size of electron acceptors on the side of photosystem II (PSII) and a decrease in net photosynthesis.

This was ascertained on the interaction effects between shade and irrigation-fertilization on LAR at early vegetative stage. Hence, LAR was significantly reduced on abaca plants grown in 0% shade due to the photooxidative damage on most leaves at seedling stage. The burning led to the reduction on the number of leaves per plant which ultimately reduced the cumulative leaf area at the start of the early vegetative stage. The application of irrigation and NPK fertilization allowed the plant to recuperate from the stress. However, the new developing leaves stopped growing and became compactly crowded at the apex of the pseudostem (see SP2A Supporting Information). This morphological response directly affected leaf dry matter and ultimately the LAR and NAR. At late vegetative stage, the NAR was higher in 0% shade (full sunlight) than in other shade treatments. This was also the stage of plant growth where CGR was highest in all treatments. The data on field documentation showed that re-greening of chlorotic leaves developed over the surface but did not eliminate the chlorosis completely (see SP2A of Supplementary Information). According to

Kamaluddin and Grace (1991) chlorophyll bleaching as a result of photooxidative damage (see SP1 of Supplementary Information), usually reached its maximum by the time the pool size electron acceptors had increased to its maximum and the recovery from photoinhibition had proceeded substantially as indicated by an increase in net photosynthesis. Such response of bleaching and recovery has also been reported in *Citrus* (Syvertsen and Smith, 1984) and *Bischofia* (Kamaluddin and Grace, 1991). Consequently, the growth and biomass production of abaca plants grown under full sunlight were negatively affected by high radiation due to photoinhibition during the seedling and early vegetative stages. The plants were able to recuperate and improve their net assimilation rate at the late vegetative stage but physiological recovery was not enough in order to exceed or even equal the productivity (i.e., biomass and fiber yield) of abaca grown in the 50% shade.

Furthermore, if shading is viewed as a way to cool the leaves and reduce the vapor pressure deficit, differences in surface air temperature (mean of 1.64 °C in 30%, 2.76 °C in 40% and 3.50 °C in 50% shade) among shaded treatments with reference to open or 0% shade treatment during midday (10:00 am – 14:00 pm) is another factor that might affect photosynthetic productivity. In the study of Raveh et al. (2003) on young citrus trees (*Citrus reticulata* B. x *Citrus sinensis* L.) under reduced radiation load due to shading revealed that midday depression of conductance and assimilation was reduced during summer or long dry periods thereby increasing photosynthetic activity. Cannell (1985) found that net photosynthetic rate of arabica coffee decreased markedly at leaf temperatures above 25°C. Both studies support the result of this research that the difference in surrounding temperature on abaca plants grown in 50% light (mean of 27°C) compared to 100% light (mean of 31°C) during dry periods may influence the growth performance of the crop. It was recorded that abaca planted in 50% shade were taller and healthier compared to the plants grown in 0% shade which were stunted and chlorotic. Hence, the combined effect of high temperature (midday depression) and solar radiation significantly affected the morphological and physiological performance of the crop if grown in full sunlight.

The superior productivity of abaca that was consistently observed in plots with NPK fertilization across shade treatments could be attributed to osmoregulation process. Osmoregulation is a process that affects water transport in the xylem that maintains high daily cell turgor pressure which affects cell elongation for growth (Saifuddin et al., 2010) and most importantly it regulates the opening and closing of the stomata which effects transitional cooling and carbon dioxide uptake for photosynthesis (Yang and Zhang, 2006). Tables S1 to S6 show the NPK absorption among abaca organs as affected by shade and irrigation-fertilization; respectively, at different stages of crop growth (Supplementary Information). Saifuddin et al. (2010) revealed that the positive effect of shade on the growth performance of *Bougainvillea glabra* in 50% and 75% shade was due to high potassium availability in the leaves which may be in charge to increase cell elongation as well as stomatal conductance. Hossain et al. (2010) found out that NPK fertilization increased plant height and photosynthesis of kenaf (*Hibiscus cannavinus*) plants leading to higher biomass accumulation. Some published documents also revealed that low NPK nutrition on plants caused lower photosynthetic rates and slower leaf expansion (Evans, 1983; Field and Mooney, 1986; Gerik et al., 1998; Zhao et al., 2003).

Finally, the combined effect of photoinhibition (Kamaluddin and Grace, 1991) and midday depression (Raveh et al., 2003) on abaca plants grown in full sunlight has stimulated the plant to acclimate both morphologically and physiologically, which has been found in most shade tolerant species (Valladares and Niinemets, 2008). Based on the results of this study, the influence of shade has some widespread implications on abaca growth and productivity under conditions of high temperature and solar radiation which is common in tropical countries like the Philippines. Furthermore, the results may provide benchmark information on how to mitigate the impact of increasing temperature due to green house effect on abaca fiber production.

2.5 Conclusions

This study was conducted to investigate the effect of shade on abaca's morphological and physiological performance. Likewise, to examine if irrigation and fertilizer application could offset the effect of shade on vegetative growth of abaca. Lastly, to identify possible interaction effects between shade and irrigation-fertilization on the morphological and physiological parameters measured. Based on the results of this study, the following conclusions are generated:

(a) shade consistently and positively affected the morphological and physiological growth parameters of abaca planted in shaded treatments from seedling stage to flagleaf stage where 50% shade provides superior growth performance and productivity;

(b) the superior productivity of abaca in response to reduced light levels was due to the avoidance of photoinhibition and photooxidation damage that negatively affected the plants grown in full sunlight (0% shade) at seedling stage and early vegetative stage which cannot be minimized or neutralized by irrigation and fertilizer application; and

(c) two-factor interaction effects between shade and irrigation-fertilization treatments on leaf area ratio was identified at early vegetative stage and flagleaf stage of crop growth.

2.6 Acknowledgement

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2.7 References

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2.8 Supplementary Information

Burned leaves at 2 weeks after planting

Extremely damaged leaves at 1 MAP

Chlorotic leaves at 3 MAP (month after planting)

Reduction on the number of leaves at 4 MAP

SP1 Abaca plants grown in 0% shade (full sunlight) with burned and extremely damaged leaves due to high radiation or temperature

A

B

SP2 Abaca plants where new developing leaves stopped growing and became compactly crowded at the apex of the pseudostem at 6 MAP (early vegetative stage) Note: the re-greening of old chlorotic leaves that developed over the surface but did not eliminate the chlorosis and usually mistakenly identified as bunchy top disease in the field (A). Stunted and chlorotic abaca plants in 0% shade with irrigation and fertilization at 12 months after planting (B).

Table S1 Nitrogen absorption (g plant^{-1}) among abaca organs at different developmental stages as affected by shade across irrigation-fertilization treatments

Plant Organs	Shading Treatments	Stages of Plant Growth			
		Seedling	Early vegetative	Late vegetative	Flagleaf
Leaves	0% shade	47.2±18.4^{b}	66.3±37.3^{b}	217.5±63.9^{a}	-15.1±45.8^{b}
	30% shade	103.7±18.4^{a}	167.0±37.3^{a}	245.7±63.9^{a}	-69.6±45.8^{b}
	40% shade	88.6±18.4^{ab}	200.0±37.3^{a}	151.6±63.9^{a}	210.1±45.8^{a}
	50% shade	139.7±18.4^{a}	180.1±37.3^{a}	451.9±63.9^{a}	251.0±45.8^{a}
Leafstalks	0% shade	3.7±1.5^{c}	11.1±5.1^{b}	26.5±6.4^{b}	-0.8±7.3^{b}
	30% shade	8.6±1.5^{b}	27.4±5.1^{a}	23.0±6.4^{b}	4.5±7.3^{ab}
	40% shade	7.4±1.5^{bc}	30.8±5.1^{a}	13.5±6.4^{b}	14.6±7.3^{ab}
	50% shade	13.3±1.5^{a}	22.7±5.1^{ab}	47.1±6.4^{a}	24.1±7.3^{a}
Pseudostem	0% shade	16.9±7.0^{c}	52.0±16.9^{b}	121.3±23.9^{b}	86.0±27.7^{b}
	30% shade	38.6±7.0^{ab}	92.0±16.9^{ab}	103.9±23.9^{b}	112.1±27.7^{ab}
	40% shade	33.1±7.0^{ac}	92.5±16.9^{ab}	82.6±23.9^{b}	174.6±27.7^{a}
	50% shade	58.2±7.0^{a}	122.5±16.9^{a}	196.7±23.9^{a}	150.8±27.7^{ab}
Corm	0% shade	11.8±3.0^{a}	12.8±6.0^{b}	47.7±7.0^{a}	21.5±6.3^{a}
	30% shade	18.3±3.0^{a}	28.4±6.0^{ab}	19.0±7.0^{b}	23.1±6.3^{a}
	40% shade	14.1±3.0^{a}	38.9±6.0^{a}	12.9±7.0^{b}	56.8±6.3^{a}
	50% shade	17.7±3.0^{a}	33.9±6.0^{a}	55.8±7.0^{a}	34.5±6.3^{a}
Roots	0% shade	11.8±5.0^{b}	7.8±7.1^{b}	33.4±8.8^{a}	34.9±8.5^{b}
	30% shade	27.7±5.0^{a}	22.8±7.1^{ab}	23.3±8.8^{a}	35.4±8.5^{b}
	40% shade	27.4±5.0^{a}	42.1±7.1^{a}	23.8±8.8^{a}	57.4±8.5^{a}
	50% shade	40.7±5.0^{a}	43.3±7.1^{a}	37.6±8.8^{a}	60.7±8.5^{a}

Note**:** Least squares means in each column within the cell with different letter superscripts (a-c) are significantly different at $p<0.05$, n = 16

Table S2 Nitrogen absorption (g plant^{-1}) among abaca organs at different developmental stages as affected by irrigation (I) and fertilizer (F) application across shade treatments

Plant Organs	Irrigation and Fertilizer Treatments	Stages of Plant Growth			
		Seedling	Early vegetative	Late vegetative	Flagleaf
Leaves	Without I and F	59.3±18.4^{b}	104.2±37.3^{a}	143.4±63.9^{a}	112.4±45.8^{ab}
	Without I, with F	106.8±18.4^{ab}	194.0±37.3^{a}	382.8±63.9^{a}	-14.6±45.8^{b}
	With I, without F	84.7±18.4^{ab}	108.6±37.3^{a}	266.7±63.9^{a}	166.5±45.8^{a}
	With I and F	128.4±18.4^{a}	206.4±37.3^{a}	273.8±63.9^{a}	112.2±45.8^{ab}
Leafstalks	Without I and F	5.9±1.5^{b}	15.7±5.1^{a}	7.7±6.4^{b}	9.4±7.3^{a}
	Without I, with F	9.3±1.5^{ab}	31.8±5.1^{a}	46.7±6.4^{a}	-4.5±7.3^{a}
	With I, without F	6.6±1.5^{b}	15.8±5.1^{a}	27.7±6.4^{a}	15.6±7.3^{a}
	With I and F	11.2±1.5^{a}	28.6±5.1^{a}	27.7±6.4^{a}	22.0±7.3^{a}
Pseudostem	Without I and F	26.4±7.0^{a}	53.6±16.9^{b}	50.5±23.9^{c}	146.2±27.7^{a}
	Without I, with F	45.0±7.0^{a}	123.8±16.9^{a}	187.5±23.9^{a}	85.5±27.7^{a}
	With I, without F	29.4±7.0^{a}	61.0±16.9^{b}	105.8±23.9^{bc}	127.0±27.7^{a}
	With I and F	45.9±7.0^{a}	120.8±16.9^{a}	160.8±23.9^{ab}	164.7±27.7^{a}
Corm	Without I and F	9.8±3.0^{c}	20.6±6.0^{a}	27.1±7.0^{a}	40.7±6.3^{a}
	Without I, with F	19.2±3.0^{ab}	37.6±6.0^{a}	49.8±7.0^{a}	26.0±6.3^{a}
	With I, without F	11.8±3.0^{bc}	25.0±6.0^{a}	29.6±7.0^{a}	27.7±6.3^{a}
	With I and F	21.1±3.0^{a}	30.9±6.0^{a}	28.9±7.0^{a}	41.5±6.3^{a}
Roots	Without I and F	17.0±5.0^{b}	22.8±7.1^{a}	23.4±8.8^{a}	46.1±8.5^{a}
	Without I, with F	31.7±5.0^{ab}	38.5±7.1^{a}	38.5±8.8^{a}	35.1±8.5^{a}
	With I, without F	24.4±5.0^{ab}	20.2±7.1^{a}	31.4±8.8^{a}	48.3±8.5^{a}
	With I and F	34.5±5.0^{a}	34.5±7.1^{a}	24.8±8.8^{a}	59.0±8.5^{a}

Note**:** Least squares means in each column within the cell with different letter superscripts (a-c) are significantly different at $p<0.05$, n = 16

Table S3 Phosphorus absorption (g plant^{-1}) among abaca organs at different developmental stages as affected by shade across irrigation-fertilization treatments

Plant Organs	Shading Treatments	Stages of Plant Growth			
		Seedling	Early vegetative	Late vegetative	Flagleaf
Leaves	0% shade	4.6±1.9^{b}	6.9±4.0^{b}	28.6±6.7^{a}	-2.7±6.1^{b}
	30% shade	10.6±1.9^{a}	17.1±4.0^{ab}	24.9±6.7^{a}	-8.8±6.1^{b}
	40% shade	10.0±1.9^{a}	23.0±4.0^{a}	19.0±6.7^{a}	28.9±6.1^{a}
	50% shade	13.8±1.9^{a}	21.3±4.0^{a}	44.6±6.7^{a}	34.4±6.1^{a}
Leafstalks	0% shade	1.3±0.5^{c}	3.6±1.6^{b}	10.2±2.0^{a}	-0.3±2.3^{b}
	30% shade	3.1±0.5^{ab}	7.4±1.6^{a}	8.4±2.0^{a}	-0.1±2.3^{b}
	40% shade	2.7±0.5^{bc}	9.7±1.6^{a}	6.7±2.0^{a}	6.3±2.3^{ab}
	50% shade	4.3±0.5^{a}	7.1±1.6^{ab}	11.7±2.0^{a}	8.4±2.3^{a}
Pseudostem	0% shade	3.9±2.1^{b}	17.6±5.2^{b}	37.1±7.2^{a}	19.6±7.1^{b}
	30% shade	11.8±2.1^{a}	24.7±5.2^{ab}	40.4±7.2^{a}	39.1±7.1^{ab}
	40% shade	11.6±2.1^{a}	32.0±5.2^{ab}	32.9±7.2^{a}	48.0±7.1^{a}
	50% shade	16.8±2.1^{a}	39.4±5.2^{a}	48.7±7.2^{a}	34.7±7.1^{ab}
Corm	0% shade	1.3±0.6^{b}	2.2±1.0^{b}	6.7±1.2^{b}	4.7±1.2^{a}
	30% shade	3.4±0.6^{a}	5.4±1.0^{ab}	4.6±1.2^{b}	4.5±1.2^{a}
	40% shade	2.6±0.6^{ab}	6.1±1.0^{a}	3.9±1.2^{b}	11.2±1.2^{a}
	50% shade	3.6±0.6^{a}	5.2±1.0^{a}	11.3±1.2^{a}	5.9±1.2^{a}
Roots	0% shade	1.2±0.6^{b}	1.1±0.8^{b}	4.4±0.9^{a}	4.9±1.1^{a}
	30% shade	3.1±0.6^{a}	2.8±0.8^{ab}	3.5±0.9^{a}	4.3±1.1^{a}
	40% shade	2.9±0.6^{a}	4.6±0.8^{a}	2.9±0.9^{a}	8.0±1.1^{a}
	50% shade	4.3±0.6^{a}	4.9±0.8^{a}	4.0±0.9^{a}	7.6±1.1^{a}

***Note*:** Least squares means in each column within the cell with different letter superscripts (a-c) are significantly different at $p<0.05$, n = 16

Table S4 Phosphorus absorption (g plant^{-1}) among abaca organs at different developmental stages as affected by irrigation (I) and fertilizer (F) application across shade treatments

Plant Organs	Irrigation and Fertilizer Treatments	Stages of Plant Growth			
		Seedling	Early vegetative	Late vegetative	Flagleaf
Leaves	Without I and F	6.2±1.9^{b}	13.0±4.0^{a}	15.8±6.7^{b}	16.1±6.1^{ab}
	Without I, with F	11.0±1.9^{a}	21.2±4.0^{a}	43.3±6.7^{a}	-1.5±6.1^{b}
	With I, without F	8.6±1.9^{a}	12.2±4.0^{a}	29.3±6.7^{ab}	22.1±6.1^{a}
	With I and F	13.2±1.9^{a}	22.0±4.0^{a}	28.6±6.7^{ab}	15.1±6.1^{ab}
Leafstalks	Without I and F	2.1±0.5^{b}	5.2±1.6^{a}	5.1±2.0^{b}	4.6±2.3^{a}
	Without I, with F	2.5±0.5^{b}	8.3±1.6^{a}	13.7±2.0^{a}	-2.1±2.3^{a}
	With I, without F	2.5±0.5^{b}	6.0±1.6^{a}	9.4±2.0^{ab}	6.3±2.3^{a}
	With I and F	4.2±0.5^{a}	8.2±1.6^{a}	8.9±2.0^{ab}	5.5±2.3^{a}
Pseudostem	Without I and F	8.1±2.1^{a}	17.5±5.2^{c}	21.4±7.2^{b}	38.6±7.1^{a}
	Without I, with F	13.1±2.1^{a}	36.4±5.2^{ab}	50.5±7.2^{a}	17.4±7.1^{a}
	With I, without F	9.8±2.1^{a}	21.9±5.2^{bc}	34.8±7.2^{ab}	36.6±7.1^{a}
	With I and F	13.1±2.1^{a}	37.8±5.2^{a}	52.4±7.2^{a}	48.8±7.1^{a}
Corm	Without I and F	1.9±0.6^{a}	3.4±1.0^{a}	5.1±1.2^{a}	7.5±1.2^{a}
	Without I, with F	3.2±0.6^{a}	5.5±1.0^{a}	7.1±1.2^{a}	5.1±1.2^{a}
	With I, without F	2.1±0.6^{a}	4.9±1.0^{a}	8.4±1.2^{a}	5.4±1.2^{a}
	With I and F	3.7±0.6^{a}	5.1±1.0^{a}	5.8±1.2^{a}	8.3±1.2^{a}
Roots	Without I and F	1.8±0.6^{a}	2.6±0.8^{a}	2.9±0.9^{a}	6.1±1.1^{a}
	Without I, with F	3.0±0.6^{a}	4.2±0.8^{a}	4.4±0.9^{a}	4.6±1.1^{a}
	With I, without F	2.6±0.6^{a}	2.4±0.8^{a}	3.6±0.9^{a}	6.7±1.1^{a}
	With I and F	4.0±0.6^{a}	4.2±0.8^{a}	3.9±0.9^{a}	7.3±1.1^{a}

***Note*:** Least squares means in each column within the cell with different letter superscripts (a-c) are significantly different at $p<0.05$, n = 16

Table S5 Potassium absorption (g plant^{-1}) among abaca organs at different developmental stages as affected by shade across irrigation-fertilization treatments

Plant Organs	Shading Treatments	Stages of Plant Growth			
		Seedling	Early vegetative	Late vegetative	Flagleaf
Leaves	0% shade	44.0±21.4^{b}	88.0±34.8^{a}	373.2±80.6^{a}	-21.7±56.7^{b}
	30% shade	114.2±21.4^{a}	142.8±34.8^{a}	310.8±80.6^{a}	-100.1±56.7^{b}
	40% shade	133.4±21.4^{a}	183.5±34.8^{a}	238.1±80.6^{a}	239.9±56.7^{a}
	50% shade	142.9±21.4^{a}	97.4±34.8^{a}	486.2±80.6^{a}	285.1±56.7^{a}
Leafstalks	0% shade	12.9±8.0^{c}	52.7±21.8^{b}	235.9±50.7^{a}	-0.5±30.9^{b}
	30% shade	37.9±8.0^{ab}	104.8±21.8^{ab}	202.1±50.7^{a}	-4.4±30.9^{b}
	40% shade	51.5±8.0^{bc}	123.3±21.8^{a}	168.1±50.7^{a}	76.2±30.9^{ab}
	50% shade	67.1±8.0^{a}	41.2±21.8^{b}	344.5±50.7^{a}	109.0±30.9^{a}
Pseudostem	0% shade	49.6±27.0^{b}	221.7±55.1^{a}	824.1±161.0^{a}	603.0±128.9^{a}
	30% shade	157.7±27.0^{a}	229.1±55.1^{a}	796.7±161.0^{a}	533.3±128.9^{a}
	40% shade	188.7±27.0^{a}	290.0±55.1^{a}	771.6±161.0^{a}	727.8±128.9^{a}
	50% shade	201.5±27.0^{a}	205.8±55.1^{a}	1189.2±161.0^{a}	536.8±128.9^{a}
Corm	0% shade	21.2±7.6^{b}	40.8±14.7^{ab}	161.7±24.7^{a}	66.1±11.4^{ab}
	30% shade	57.1±7.6^{a}	76.4±14.7^{a}	99.1±24.7^{ab}	36.8±11.4^{b}
	40% shade	38.7±7.6^{ab}	81.0±14.7^{a}	72.4±24.7^{b}	89.0±11.4^{a}
	50% shade	42.8±7.6^{a}	31.2±14.7^{b}	155.5±24.7^{a}	33.6±11.4^{b}
Roots	0% shade	33.6±15.8^{b}	26.5±13.4^{b}	200.7±36.8^{a}	157.6±33.7^{a}
	30% shade	75.9±15.8^{a}	48.7±13.4^{ab}	135.8±36.8^{a}	125.6±33.7^{a}
	40% shade	86.7±15.8^{a}	82.8±13.4^{a}	128.7±36.8^{a}	239.0±33.7^{a}
	50% shade	120.6±15.8^{a}	48.2±13.4^{ab}	160.1±36.8^{a}	226.9±33.7^{a}

***Note*:** Least squares means in each column within the cell with different letter superscripts (a-c) are significantly different at p<0.05, n = 16

Table S6 Potassium absorption (g plant^{-1}) among abaca organs at different developmental stages as affected by irrigation (I) and fertilizer (F) application across shade treatments

Plant Organs	Irrigation and Fertilizer Treatments	Stages of Plant Growth			
		Seedling	Early vegetative	Late vegetative	Flagleaf
Leaves	Without I and F	65.0±21.4^{b}	93.4±34.8^{a}	186.5±80.6^{b}	142.3±56.7^{a}
	Without I, with F	113.1±21.4^{ab}	136.0±34.8^{a}	537.5±80.6^{a}	-32.6±56.7^{a}
	With I, without F	91.1±21.4^{b}	114.0±34.8^{a}	328.8±80.6^{ab}	173.1±56.7^{a}
	With I and F	165.3±21.4^{a}	168.3±34.8^{a}	355.6±80.6^{ab}	120.3±56.7^{a}
Leafstalks	Without I and F	30.3±8.0^{b}	28.2±21.8^{b}	122.8±50.7^{b}	50.8±30.9^{a}
	Without I, with F	42.0±8.0^{b}	133.3±21.8^{a}	358.1±50.7^{a}	-23.3±30.9^{a}
	With I, without F	31.6±8.0^{b}	29.8±21.8^{b}	223.6±50.7^{ab}	76.8±30.9^{a}
	With I and F	65.5±8.0^{a}	130.7±21.8^{a}	246.0±50.7^{ab}	76.0±30.9^{a}
Pseudostem	Without I and F	91.3±27.0^{b}	145.0±55.1^{b}	482.5±161.1^{b}	578.2±128.9^{a}
	Without I, with F	167.4±27.0^{ab}	299.0±55.1^{ab}	1151.6±161.1^{a}	412.7±128.9^{a}
	With I, without F	115.4±27.0^{b}	166.0±55.1^{b}	852.4±161.1^{ab}	710.2±128.9^{a}
	With I and F	223.4±27.0^{a}	336.7±55.1^{a}	1095.2±161.1^{a}	699.9±128.9^{a}
Corm	Without I and F	23.6±7.6^{b}	30.1±14.7^{a}	105.5±24.7^{a}	59.7±11.4^{a}
	Without I, with F	49.9±7.6^{a}	73.5±14.7^{a}	150.5±24.7^{a}	50.0±11.4^{a}
	With I, without F	33.3±7.6^{ab}	68.7±14.7^{a}	115.5±24.7^{a}	64.8±11.4^{a}
	With I and F	53.1±7.6^{a}	57.1±14.7^{a}	117.1±24.7^{a}	51.0±11.4^{a}
Roots	Without I and F	42.8±15.8^{b}	37.8±13.4^{a}	113.9±36.8^{a}	177.5±33.7^{a}
	Without I, with F	91.8±15.8^{a}	62.4±13.4^{a}	193.3±36.8^{a}	155.6±33.7^{a}
	With I, without F	69.6±15.8^{ab}	47.2±13.4^{a}	155.2±36.8^{a}	209.6±33.7^{a}
	With I and F	112.7±15.8^{a}	58.8±13.4^{a}	162.8±36.8^{a}	206.4±33.7^{a}

***Note*:** Least squares means in each column within the cell with different letter superscripts (a-b) are significantly different at p<0.05, n = 16

3. Fiber Yield and Quality of Abaca (*Musa textilis* var*. Laylay*) Grown under Different Shade Conditions, Water and Nutrient Management

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OUTLINE AND OVERVIEW

This chapter demonstrates on how shade and irrigation-fertilization affects fiber yield, fiber recovery and fiber quality of abaca. This section shows the negative effect of photoinhibition on the morphological growth parameters (i.e., pseudostem length and girth) measured that is highly correlated to fiber yield and fiber recovery of abaca. The knowledge gap on what optimum light requirement is needed for abaca to achieve an optimum yield without affecting the quality of the fiber for industrial use is also discussed in this chapter.

Fiber Yield and Quality of Abaca (*Musa textilis* var. *Laylay*) Grown under Different Shade Conditions, Water and Nutrient Management

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ABSTRACT

The knowledge gap on the optimum light, nutrient and water requirements of abaca to attain optimum yield, and limited information on how these parameters affect fiber recovery and fiber quality under field conditions are very important for abaca production and management. Light infiltration was reduced by 30%, 40%, and 50% of full sunlight using polypropylene shade nets. Irrigation was applied at a rate of 5 liters plant^{-1} application^{-1} day^{-1}. Placement application of N, P_2O_5, K_2O using complete fertilizer was done at 14 grams plant^{-1} quarter^{-1} for the first six months and was increased to 40 grams plant^{-1} quarter^{-1} for the next six months after planting. Results revealed that abaca planted under different light regimes showed that 50% shade had significantly ($p<0.01$) higher fiber yield compared to those that were under other light treatments since the plants pseudostem under such treatment was longer, bigger and heavier. The combination of irrigation and fertilization could further enhance fiber yield to as much as 41% but this was not enough to offset the effects of shade on the physiological performance of the plant which significantly ($p<0.01$) increased fiber yield to as much as 165%. Statistical analysis showed that shade and irrigation-fertilizer application had no significant effect on fiber fineness and tensile strength. Therefore, 50% shade is the optimum requirement of abaca (var. *Laylay*) to achieve an optimum machine stripped fiber yield of 135.04±4.31 grams plant^{-1} without affecting fiber quality for industrial purposes.

Keywords: Abaca, shade plant, agroforestry, fiber crop, fiber fineness, tenacity

3.1 Introduction

Abaca (*Musa textilis* Née) is closely related to edible banana (*Musa acuminata* and *M. balbisiana*) and originates from the Philippines (Halos, 2008; Sievert, 2009). It is grown primarily for its fibers which are utilized by the pulp, cordage and fiber craft industries. The specific tensile strength of the fiber is comparative or even higher than that of fiberglass (Bledzki et al., 2007; Sinon, 2008). The car company, Daimler AG was successful in using abaca for the exterior parts of Mercedes-Benz A class passenger car (DaimlerChrysler, 2004; Oliver, 2004). In the United Kingdom, the use of abaca fiber as a replacement for asbestos has created a big boost in its demand (Armecin and Gabon, 2008). PCARRD (2003) reported that abaca has captured about 80% of the UK market on asbestos-based boards. Thus, production of high quality fiber should be increased to respond to future increase in its demand.

FIDA (2010) reported that the world consumption of abaca fibers in 2008 was 82,121 tons. The Philippines supplied 84% of the global production which is equivalent to an average fiber production of 68,982 tons yr^{-1} from 1999 to 2008, where the Eastern Visayas region (islands of Leyte, Biliran, Samar and Pana-on) was the major abaca producer that supplied an annual average of 25,517 tons or 38.5% of the total production (FIDA, 2010). The average annual yield in Southern Leyte is 913 kg fiber ha^{-1}, which is above the national annual average of 610 kg ha^{-1} but far behind the potential yield of 2000 kg of fiber ha^{-1} (Armecin et al., 2011).

In Leyte, most abaca growing areas are concentrated in the hilly lands where fiber yield and quality are low (Armecin, 2008). PCARRD (2003) reported that the lack of knowledge on the optimum light, nutrient and water requirements of abaca plants has greatly contributed to low fibre yield. To date, no scientific study has been conducted to determine the influence of shade, water and nutrient availability on fiber yield without affecting fiber quality for industrial use. Hence, this study was carried out to: (a) investigate the effect of reducing light intensities by 30%, 40% and 50% of full sunlight on fiber yield and fiber quality, and (b) determine the optimum light requirement of abaca plants to attain the optimum yield without affecting the quality of the fiber for industrial use.

3.2 Materials and methods

3.2.1 Biophysical and climatic conditions of the study site

The study site was located in an abaca farmer's area in Barangay Catmon, Ormoc City, Philippines 11° 04′ 52.4″ N and 124° 34′ 29.5″ E on an alluvial terrace with an elevation of 44.5 meters above mean sea level and a slope of 0-3%. The site has an average annual precipitation of 2,600 mm yr^{-1} and a mean annual temperature of 27.5 °C. The site was previously planted with sugarcane (*Saccharum officinarum*) and then left under fallow for ten years. Constant grazing caused grasses to dominate the vegetation structure of the site. The soil is classified a Haplic Alisol (IUSS Working Group WRB, 2006), whose clay fraction is dominated by kaolinite and halloysite and contains significant amounts of goethite and hematite with more than 60% P retention capacity (Asio, 1996; Asio et al., 1998).

The pH values for the 0-30 cm and 30-60 cm soil depths were 5.16 and 5.14, respectively. These pH values indicate strongly acidic conditions (Soil Conservation Society of America, 1982). Bulk density ranged from 1.06 g cm^{-3} to 1.11 g cm^{-3} with very minor variations in the values indicating high porosity of the soil. Furthermore, results revealed that there were no significant differences in the total nitrogen between different treatments and soil depths. Available phosphorus was much higher in the top soil (0-30 cm) than in the sub-surface soil (30-60 cm).

3.2.2 Preparation of planting materials at the nursery

Tissue cultured abaca plantlet was individually potted in a soil-filled polyethylene bag (10cm x 15cm) and placed in sealed recovery chamber for one month until new leaves (at most 3) had developed. The chamber was partially opened (1 section week^{-1}) one month after potting to acclimatize the seedlings from the outside climatic conditions. Seedlings were watered every second day. No fertilizer was applied to guarantee uniform nutritional status of the planting material prior to out-planting. Due to the rapid growth of the seedlings, re-bagging was done (15cm x 25cm polyethylene bags) two months after potting to provide more space for root development. The seedlings were hauled to the temporary nursery constructed at the middle of the study site a month after re-bagging. The process allows the planting materials to adjust to on-site climatic condition prior to out-planting. This was done for another three months where watering was minimized and light infiltration was increased (by step-wise removing the shade materials) every week. During this period, the seedlings were evaluated and classified according to plant height, girth and number of leaves. These data were basis for selecting and distributing the seedlings to treatment plots to guarantee uniform morphological characteristics of planting material.

3.2.3 Experimental design

The design of the experiment was a 4x4 factorial combination of shade and irrigation-fertilizer application (Figure 3.1). Tissue-cultured abaca seedlings (var. *Laylay*) were planted in a split-plot randomized block design with four replications. The dimension of each main plot (shade) was 30m x 30m. Since there were four sub-plots (i.e., irrigation and fertilizer application), a total of 64 plots were established with a dimension of 12.5m x12.5m plot^{-1}. The planting distance used was 2.5m x 2.5m (square method) that corresponded to a total of 36 abaca seedlings plot^{-1}.

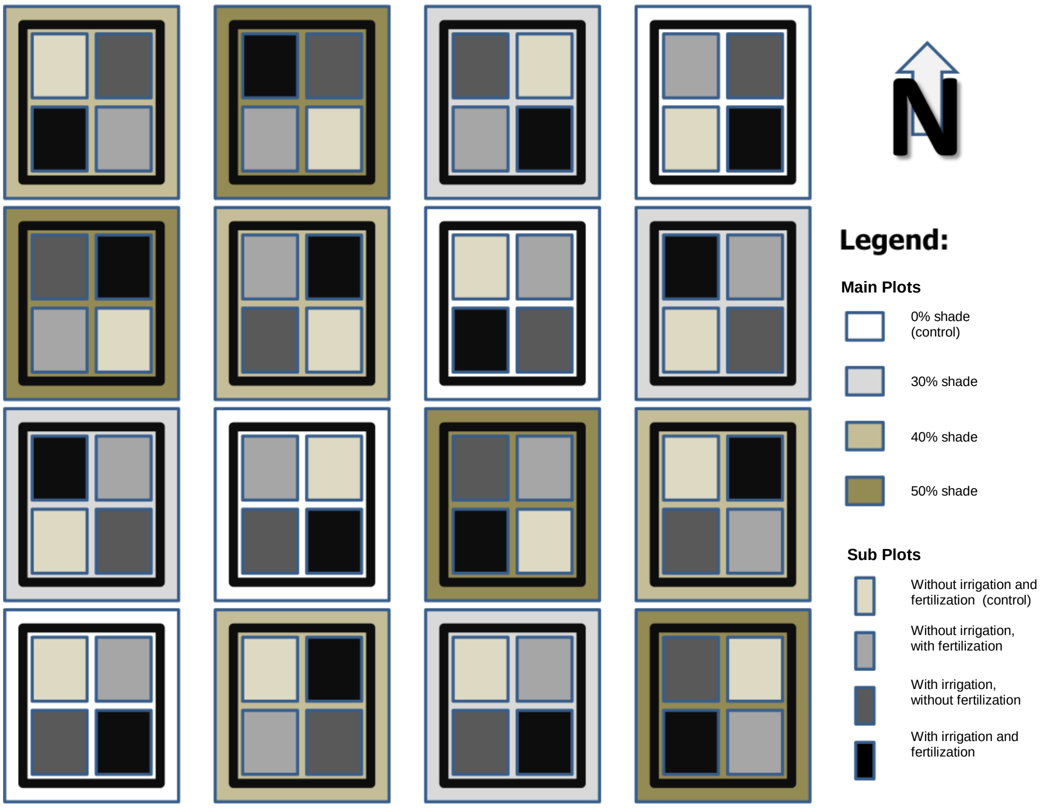

Fig. 3.1 Experimental layout of the study site

3.2.4 Installation of shade nets and drip irrigation

Three different shade nets made of polypropylene (Bayview Fishing Supply and General Merchandise, Manila, Philippines) were used: B-double (4mm x 5mm mesh size), A-double (3.5mm x 2.5mm mesh size) and dry nets (2mm x 2mm mesh size) that permitted 70%, 60%, and 50% of full sunlight, respectively. The nets were installed at an initial height of 3.7 meters and were raised to 6.0 meters seven months after planting (Figure 3.2). Photosynthetically active radiation (PAR) was measured at weekly intervals in all levels of shading using a LI-COR 190 SA quantum sensor.

Fig. 3.2 Fully installed shade nets (main treatment per replication) of the research area (Note: the photo seems to depict a depression in the middle of the study site which is not in actual condition where the slope is 0-3%)

A drip irrigation system was improvised by installing 288 20-liter water containers. One container was properly leveled and installed at the center of four abaca plants to attain uniform distribution of water among plants at a rate of 5 liters plant^{-1} application^{-1} day^{-1}. Since there was no available information on the evaporative demand of the crop in the field, irrigation was applied during the dry period when soil moisture was below 26% as determined using the gravimetric method. During the first two months after planting (MAP), the abaca plants were irrigated with 5 liters of water plant^{-1} application^{-1} day^{-1}. The frequency of irrigation was applied two times at seedling stage (1-3 MAP), three times at the early vegetative stage (4-6 MAP), four times at the late vegetative stage (7-9 MAP), and five times at flagleaf stage (10-12 MAP). The reason for increasing the frequency of watering was due to an increase of emergence of new suckers.

3.2.5 Fertilizer application

A fertilizer recommended rate of 43 kg N, P_2O_5 and K_2O per hectare for each of the fertilized plots using complete (14-14-14) fertilizer was used. This was applied in five different periods of crop growth. At planting, a blanket application of 5 grams per plant was done. At three and six months after planting, placement application of 10 grams per plant was applied. This was increased to 28 grams per plant at nine and twelve months after planting. During the conduct of the study, there was no available and published data on the critical nutritional level of abaca plant; hence, the National Abaca Research Center (NARC) and Fiber Development Authority (FIDA) recommendations were used.

3.2.6 Harvesting and fiber extraction

Abaca is usually harvested at the flagleaf stage or just before flowering. In this study, the flagleaf started to emerge from the mother plant 10-12 months after planting. Thirteen sample plants treatment^{-1} replication^{-1} were harvested, totalling to 832 matured abaca plants. The fibers were extracted using the NARC's portable machine stripper. During the tuxying of the pseudostem, the tuxy materials from the inner and outer layer were weighed separately. Fibers were classified and weighed and fiber yield plant^{-1} was determined. Fiber recovery plant^{-1} (in relation to pseudostem fresh weight) was calculated using the formula (Sinon, 2008):

$$F_{R\,(pseudostem\ fresh\ weight)} = \frac{W_F}{W_P} \times 100 \qquad (1)$$

Where: $F_{R\,(\text{pseudostem fresh weight})}$ = Stripped fiber recovery per plant (%)
W_F = Total weight of dried fiber per plant (g)
W_P = Total weight of pseudostem per plant (g)

3.2.7 Determination of fiber fineness and tenacity

The fiber tensile strength was determined by randomly selecting 10 fiber strands from each outer and inner leaf sheaths of the plant. Each fiber strand was divided into 3 parts, i.e., bottom, middle and top position. A 12-cm long sample was measured that was taken from each position. These samples were weighed and the breaking load was determined using analogous tensile strength meter (Zwick & Co., Eisingen, Germany) at 45 mm min^{-1} speed and at 0.1 kg scale setting.

Fiber fineness was determined by the Tex value common in the tensile strength industry. This is the gravimetric fineness or fiber linear density expressed in grams per 1000 meters of fiber. Tenacity or tensile strength is the force required to break a bundle of fiber equalling one Tex unit, the unit of tenacity is cN Tex^{-1}. These were calculated using the formulae (Sinon, 2008):

$$Tex = \frac{x}{12\,\text{cm}} \times \frac{100\,\text{cm}}{1\text{m}} \times 1000\,\text{m} \qquad (2)$$

$$Tenacity = \frac{cN}{Tex} \qquad (3)$$

Where: Tex = gravimetric fineness or fiber linear density
x = to the mass of the fiber in grams
cN = fiber's breaking load (kg) * 9.802 N kg^{-1} * 100 centi

3.2.8 Statistical analyses

All data were tested for normality and homogeneity using PROC Univariate of Statistical Analysis System version 9.1 (SAS, 2003). PROC GLM (General linear model) procedure was initially performed to assess the significant effects of shading, irrigation, fertilizer application and their interactions on abaca's morphology, fiber yield, fiber recovery, and fiber quality.

The final models for each response variables were analyzed but including only those significant main factors and interaction effects. Duncan multiple range test (DMRT) and least squares differences (LSD) were carried out to compare treatment means of independent variables with significant variations at probability<0.05.

3.3 Results

3.3.1 Effects of shade and irrigation-fertilization on fiber yield

The total fiber yield of abaca was significantly ($p<0.01$) influenced by different light intensities according to general linear model (GLM) procedure where reduced irradiance had significantly improved both outer and inner leaf sheath's fiber yield. The abaca planted under 50% shading had considerably higher fiber yield compared to other shade treatments (Figure 3.3). This was because the pseudostems' length, girth and weight were significantly improved when light irradiance was further reduced to 50% shade. The abaca plants harvested under 50% shade produced longer (2.29±0.10 m), bigger (16.10±0.50 cm) and heavier (10.80±0.05 kg) pseudostem than those harvested in the open (0% shade) with pseudostem's length, base girth, and weight of 1.42±0.10 m, 13.18±0.50 cm, and 5.20±0.05 kg, respectively. Fiber yield in 30% and 40% shade treatments was statistically similar but significantly lower than 50% shade and higher than those in 0% shade treatment.

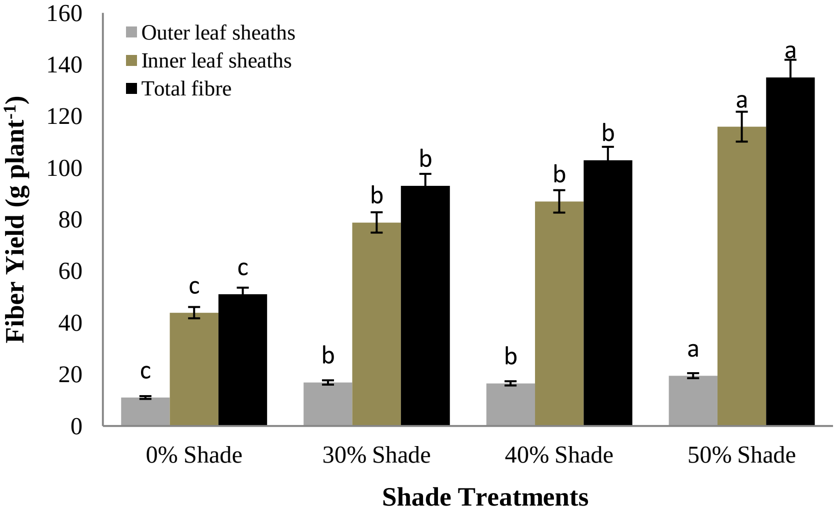

Fig. 3.3 Dried fiber yield of outer leaf sheaths, inner leaf sheaths and total (g plant-1) as affected by shade across irrigation and fertilizer application treatments (*Note: Different letter superscripts of same dependent variable among shade treatments are significantly different at p<0.05, n=208*)

The sample plants treated with NPK fertilizer had significantly higher fiber yield compared to abaca without NPK fertilization even if irrigation was provided. This is because the application of NPK fertilizer consistently and positively affected the pseudostems' length, girth and weight of the plant. The abaca harvested in plots with fertilizer application had longer (2.02±0.10 m), bigger (15.59±0.50 cm) and heavier (9.40±0.05 kg) pseudostem compared to those plants harvested in without NPK fertilization with pseudostems' length, base girth, and weight of 1.64±0.10 m, 13.29±0.50 cm, and 7.0±0.05 kg, respectively.

Furthermore, the results of statistical analysis confirmed the effect of NPK fertilizer application on fiber yield where a significant difference was observed at probability<0.01 on abaca planted in plots with fertilizer treatment. Meanwhile, there was no significant effect observed on plants grown in plots with supplemental irrigation compared to the control treatment (Figure 3.4).

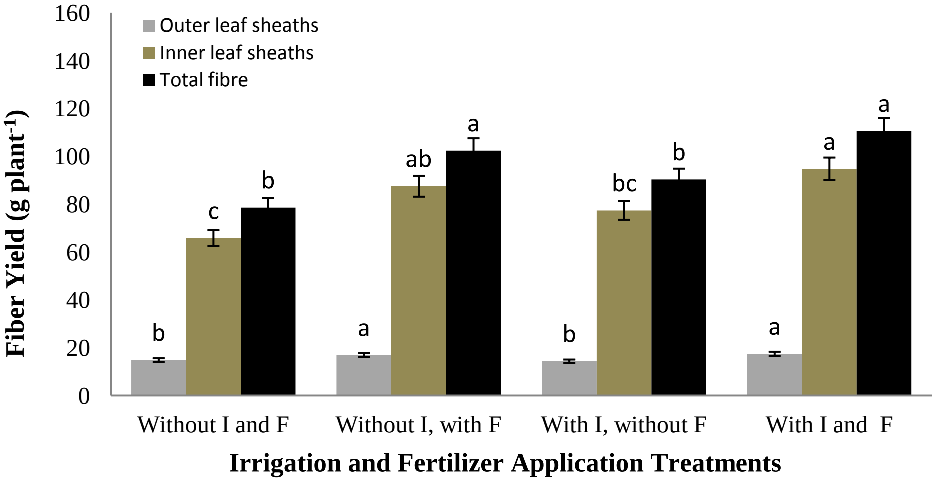

Fig. 3.4 Dried fiber yield of outer leaf sheaths, inner leaf sheaths, and total (g plant^{-1}) as affected by irrigation and fertilizer application across shade treatments (*Note: Different letter superscripts of same dependent variable among irrigation and fertilizer application treatments are significantly different at p<0.05, n=208*)

As shown in Figure 3.4, the fiber yield increased to 14% (with irrigation), 30% (with NPK fertilization), and 41% (combination of irrigation and NPK fertilizer application) compared to the sample plants without any inputs provided. It was observed that the total fiber yield in plants without any amendments (i.e., without irrigation and fertilization) is significant lower compared to those fertilized plants which is also comparable to those plants applied with irrigation water alone.

Figure 3.3, on the other hand, showed that the fiber yield constantly and positively increased to 82%, 102%, and 165% in 30%, 40% and 50% shade, respectively. This also illustrates that fiber yield of the control treatment (0% shade) is significantly lower compared to the rest of the shade treatments. Hence, Figures 3.3 and 3.4 clearly showed that the application of irrigation, fertilizer or combination of both was able to increase fiber yield but was not enough to exceed or even equal the productivity of abaca as affected by shade.

3.3.2 Effects of shade and irrigation-fertilization on fiber recovery

Table 3.1 shows that shade had positively affected ($p<0.01$) the fiber recovery of abaca. This supports the data presented in Figure 3.3 where fiber yield increased when light irradiance was reduced to as much as 50%. Statistical analysis showed that significant differences were observed on the total stripped fiber recovery among treatments as insolation was further reduced to 30%, 40%, and 50%. Hence, the increase in total fiber yield in response to shade could not only be attributed to the positive effect on the plants' morphological characteristics (i.e., pseudostem length, girth and weight) but also on its significant effect on fiber recovery.

Likewise, combination of irrigation and fertilizer application had significantly ($p<0.05$) improved fiber recovery. Results showed that there was no significant difference observed when irrigation and NPK fertilization were applied separately as individual treatment except on the outer leaf sheaths. Thus, the increase in fiber yield in response to irrigation-fertilization treatment could only be credited to the positive effect of fertilizer on the plants' morphological characteristics. This is because its influence on fiber recovery is insignificant except when irrigation and fertilizer application are combined.

Table 3.1 Stripped fiber recovery of abaca as affected by shade and irrigation-fertilization treatments

Treatments	Stripped Fiber Recovery (%)		
	Outer leaf sheaths	Inner leaf sheaths	Total
Shade			
0% shade (control)	0.16 ± 0.01^{b}	0.76 ± 0.02^{d}	0.86 ± 0.02^{d}
30% shade	0.18 ± 0.01^{a}	0.86 ± 0.02^{c}	1.01 ± 0.02^{c}
40% shade	0.18 ± 0.01^{a}	0.92 ± 0.02^{b}	1.10 ± 0.02^{b}
50% shade	0.18 ± 0.01^{a}	1.02 ± 0.02^{a}	1.20 ± 0.02^{a}
Irrigation-Fertilization			
Without I and F (control)	0.18 ± 0.01^{a}	0.84 ± 0.02^{b}	1.00 ± 0.02^{b}
Without I, with F	0.17 ± 0.01^{b}	0.89 ± 0.02^{ab}	1.04 ± 0.02^{ab}
With I, without F	0.17 ± 0.01^{b}	0.89 ± 0.02^{ab}	1.04 ± 0.02^{ab}
With I and F	0.18 ± 0.01^{a}	0.93 ± 0.02^{a}	1.09 ± 0.02^{a}

***Note*:** Least squares means in each column within the cell with different letter superscripts are significantly different at $p<0.05$ (n=208)

3.3.3 Effects of shade and irrigation-fertilization on fiber quality

The quality of the stripped fiber is an important factor to consider by the end users since it relates the quality of the end product where the fiber is used for (Sinon, 2008). In the pulp and paper industry, the color, length, texture, blade serration and cleaning are the important criteria for quality. In the cordage and car industry, strength, uniformity, fineness and ultimate fiber recovery are very important to consider. However, in this study, only fiber fineness, tensile strength, length and color were considered and measured.

The results on the tensile strength measurement revealed that the outer fiber (from outer leaf sheath) was stronger than the inner fiber (from inner leaf sheath). In addition, the top position of a single fiber strand both inner and outer has higher tensile strength compared to the middle and base position. Data showed that shade and irrigation-fertilizer application had significantly affected tensile strength at different fiber strand positions of both inner and outer leaf sheaths' fibers.

The tensile strength measurement and analysis shows that the fiber extracted from the abaca planted in 50% shade were stronger (91.62±2.35 cN Tex^{-1} inner fiber and 94.25±2.09 cN Tex^{-1} outer fiber) compared to the fiber extracted from abaca planted in 0% shade (88.17±1.67 cN Tex^{-1} inner fiber and 94.21±2.17 cN Tex^{-1} outer fiber). Based on the results, the fiber strand position was highly significant factor with direct influence on strength in relation to experimental treatments employed (Table 3.2).

With regard to fiber fineness (Tex) measurement, it was documented that inner fibers have larger fiber strands than outer fibers. The result was consistent with the study of Sinon (2011) on fiber tenacity and fineness on three abaca varieties where it was found that the inner fiber had higher Tex value compared to the outer. The optimum fiber fineness was recorded in 50% shade with mean values of 16.74 Tex and 23.20 Tex in outer and inner fiber, respectively. Statistical analysis showed that fiber strands fineness was significantly affected ($p<0.05$) by the experimental treatments applied in the study (Table 3.3).

Statistical analysis showed that significant differences were observed on fiber fineness among different positions of both outer and inner fiber strands as insolation was further reduced to 50%. However, there was no significant difference observed when irrigation and NPK fertilization were applied separately as individual treatment except when these are combined as one treatment.

Table 3.2 Fiber tensile strength of outer and inner leaf sheaths at different fiber strand positions as affected by shade and irrigation-fertilization treatments

Treatments	**Tenacity (cN Tex^{-1})**					
	Outer Leaf Sheaths' Fiber Strand Position			**Inner Leaf Sheaths' Fiber Strand Position**		
	Top	**Middle**	**Base**	**Top**	**Middle**	**Base**
Shade						
0% shade	110.39 ± 2.46^{a}	94.79 ± 1.69^{b}	77.44 ± 1.62^{b}	88.63 ± 2.81^{c}	93.71 ± 1.73^{a}	82.16 ± 1.44^{a}
30% shade	102.73 ± 2.37^{a}	96.39 ± 1.75^{b}	85.17 ± 1.56^{a}	97.73 ± 2.70^{b}	98.37 ± 1.80^{a}	83.26 ± 1.38^{a}
40% shade	106.56 ± 2.37^{a}	103.03 ± 1.62^{a}	81.32 ± 1.56^{a}	108.40 ± 2.70^{a}	98.67 ± 1.67^{a}	74.89 ± 1.38^{b}
50% shade	103.77 ± 2.37^{a}	97.13 ± 1.62^{b}	81.85 ± 1.56^{a}	94.56 ± 2.70^{bc}	99.78 ± 1.67^{a}	81.50 ± 1.38^{a}
Irrigation-Fertilization						
Without I and F	98.58 ± 2.46^{b}	95.18 ± 1.75^{b}	88.04 ± 1.62^{a}	94.57 ± 2.81^{b}	96.14 ± 1.80^{a}	83.08 ± 1.44^{a}
Without I, with F	109.13 ± 2.37^{a}	102.37 ± 1.62^{a}	79.69 ± 1.56^{bc}	98.45 ± 2.70^{ab}	100.69 ± 1.67^{a}	79.14 ± 1.38^{a}
With I, without F	110.14 ± 2.37^{a}	92.70 ± 1.69^{b}	76.26 ± 1.56^{c}	92.03 ± 2.70^{b}	95.46 ± 1.73^{a}	78.66 ± 1.38^{a}
With I and F	105.60 ± 2.37^{a}	101.08 ± 1.62^{a}	81.78 ± 1.56^{b}	104.26 ± 2.70^{a}	98.24 ± 1.67^{a}	79.94 ± 1.38^{a}

Note: Least squares means in each column within the cell with different letter superscripts are significantly different at $p<0.05$ (n=160)

Table 3.3 Fiber fineness of outer and inner leaf sheaths at different fiber strand positions as affected by shade and irrigation-fertilization treatments

Treatments	Linear Density (Tex)					
	Outer Leaf Sheaths' Fiber Strand Position			Inner Leaf Sheaths' Fiber Strand Position		
	Top	Middle	Base	Top	Middle	Base
Shade						
0% shade	10.07 ± 0.27^{a}	14.99 ± 0.35^{a}	23.29 ± 0.53^{ab}	11.68 ± 0.44^{b}	19.22 ± 0.61^{b}	26.87 ± 0.80^{b}
30% shade	9.61 ± 0.26^{a}	15.01 ± 0.37^{a}	21.73 ± 0.51^{c}	12.76 ± 0.42^{b}	22.74 ± 0.63^{a}	28.03 ± 0.77^{b}
40% shade	9.24 ± 0.26^{a}	15.32 ± 0.34^{a}	22.77 ± 0.51^{bc}	12.06 ± 0.42^{b}	20.19 ± 0.58^{b}	28.14 ± 0.77^{b}
50% shade	9.81 ± 0.26^{a}	15.87 ± 0.34^{a}	24.56 ± 0.51^{a}	14.05 ± 0.42^{a}	23.98 ± 0.58^{a}	31.56 ± 0.77^{a}
Irrigation-Fertilization						
Without I and F	9.75 ± 0.27^{ab}	15.32 ± 0.37^{a}	21.73 ± 0.53^{b}	12.62 ± 0.44^{a}	21.26 ± 0.63^{ab}	27.64 ± 0.80^{b}
Without I, with F	9.68 ± 0.26^{ab}	15.49 ± 0.34^{a}	23.97 ± 0.51^{a}	11.96 ± 0.42^{a}	20.57 ± 0.58^{b}	28.41 ± 0.77^{b}
With I, without F	9.07 ± 0.26^{b}	15.12 ± 0.35^{a}	22.35 ± 0.51^{b}	12.81 ± 0.42^{a}	21.29 ± 0.61^{ab}	27.57 ± 0.77^{b}
With I and F	10.23 ± 0.26^{a}	15.26 ± 0.34^{a}	24.29 ± 0.51^{a}	13.15 ± 0.42^{a}	23.02 ± 0.58^{a}	30.98 ± 0.77^{a}

Note: Least squares means in each column within the cell with different letter superscripts are significantly different at $p<0.05$ (n=160)

Fiber length was strongly ($p<0.01$) affected by the experimental factors (Figure 3.5) which was mainly attributed to the pseudostem or stalk's length of the sample plant as influenced by the treatments applied. Alcober (1986) reported that longer stalks generally have longer leaf sheaths from which longer fiber can be extracted. There was no negative effect documented on fiber color in relation to shading, irrigation and NPK fertilization during fiber extraction. However, it was observed that the outer fiber had darker color compared to inner fiber.

It is also worth mentioning that the percent share of outer fiber in relation to the total fiber yield decreases from 21% in 0% shade to 18%, 16%, and 14% in 30%, 40%, and 50% shade, respectively. However, the application of irrigation and NPK fertilizer will reduce the percent share of outer fiber from 19% to 16%. This indicates that shading could improve the percentage of white fiber during extraction. Hence, increase in production of high quality fiber.

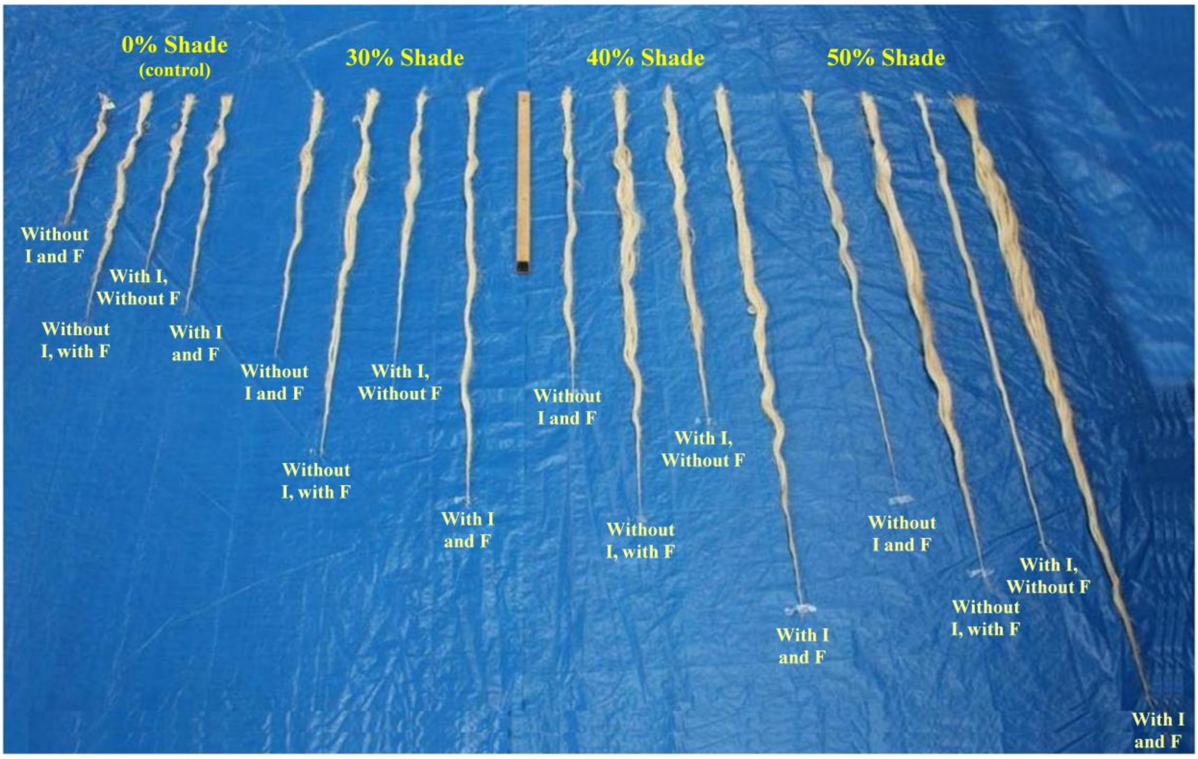

Fig. 3.5 Average fiber length of the sample plants in relation to pseudostem's length as influenced by shade, irrigation (I) and fertilizer (F) application

3.3.4 Interaction effects

The results of the statistical analysis revealed that there was a two-factor interaction effect of shade and irrigation-fertilizer application treatments on outer leaf sheaths' fiber yield (probability=0.013), inner leaf sheaths' fiber yield (probability=0.001) and total fiber yield (probability=0.001). These two-factor interactions are supported by the data presented on Figures 3.3 and 3.4 where outer, inner and total fiber yield were significantly affected by shade and irrigation-fertilizer application. Figure 3.6 showed that the interaction of shade and irrigation-fertilizer application treatments was evident in 30% and 50% shade. These are the two shade treatments where the available incident radiation for plant growth significantly varies, i.e., higher in 30% and extremely lower in 50%. Hence, water and nutrient availability are critical. Furthermore, irrigation plays an important role than NPK fertilization at 0% shade (control treatment) in increasing fiber yield.

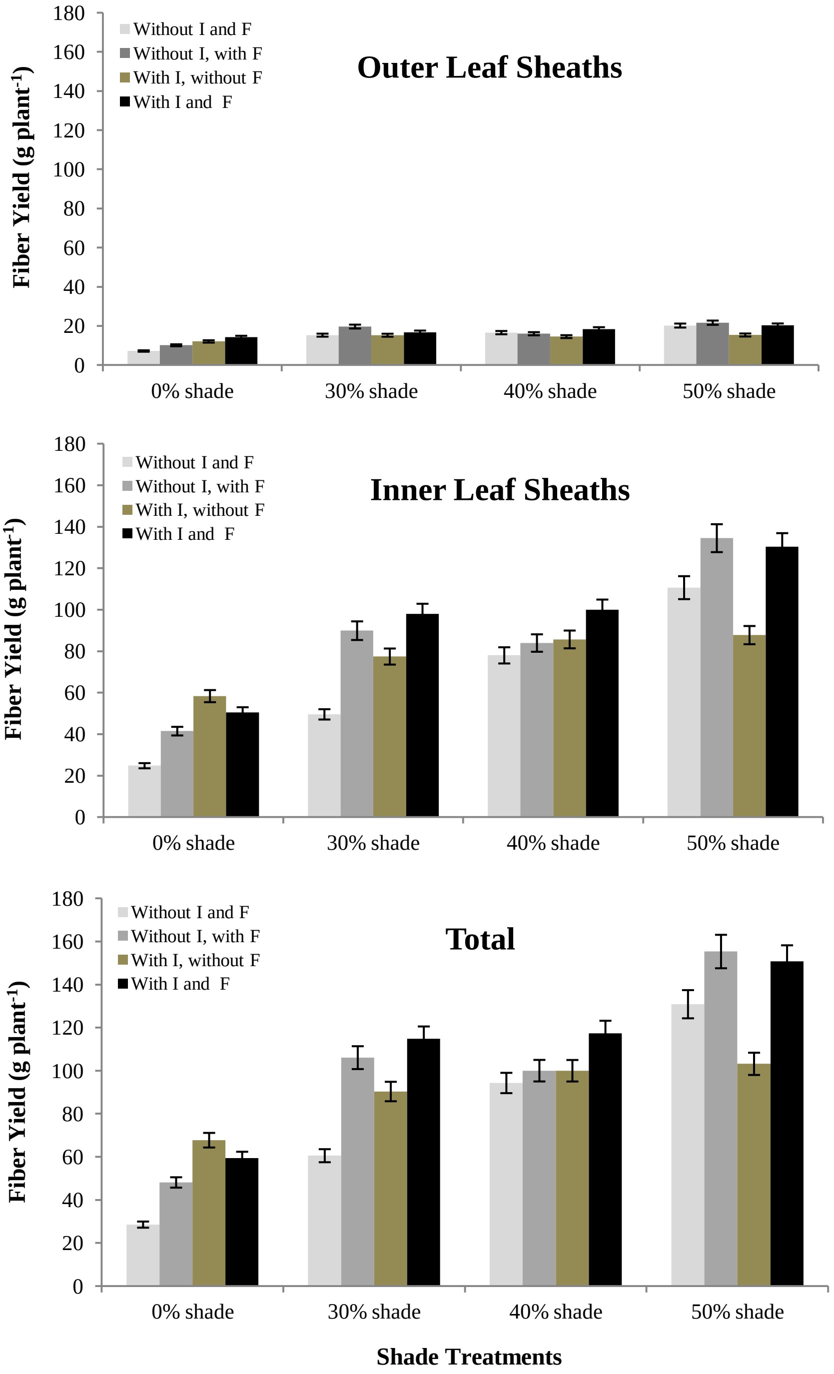

Fig. 3.6 Two factor interaction effects of shade and irrigation-fertilizer application treatments on outer leaf sheaths dried fiber, inner leaf sheaths dried fiber, and total dried fiber

3.4 Discussion

The major result of the study was the superior productivity of abaca in response to increasing shade. Horticultural measurements during harvest revealed that abaca plants grown under 50% shade have taller, bigger, and heavier stalks (pseudostem) resulting in higher yield (g plant^{-1}) compared to abaca harvested from other light treatments. The results are in accordance with the findings of Batugal et al. (1977) on abaca (variety *Tinawagang puti*) where improved growth and yield was recorded under 66% light. Torquebiau and Akeampong (1994) and Senevirathna et al. (2008) studying edible banana (*Musa x paradisiaca*) under different irradiance documented the highest biomass and yield at 50% light. While Söndahl et al. (2005) recommended that overhead shade in arabica coffee (*Coffea arabica*) should not exceed 50% of total irradiance to attain optimum yield. Furthermore, Alcober (1986) reported that fiber yield depends on the number of harvestable stalks and the physical characters of the stalks at harvest. He found out that there was a significant correlation between stalk weight, length and fiber yield. This was consistent with the result in this study where there were highly significant correlations between fiber yield and pseudostem or stalk weight (r=0.93) and length (r=0.87).

The results on fiber recovery calculation showed highly significant correlation between fiber recovery and stalk's length (r=0.84) and girth (r=0.78). Alemania et al. (1982) found that the lower fiber recovery of *inosa* and *laylay* varieties was compensated by its bigger stalks compared to *linawaan* variety where the fiber yield (g plant^{-1}) of the former equalled to the fiber yield of the latter. The data on fiber recovery (Table 3.1) also revealed that outer leaf sheaths had lower fiber recovery. Alemania et al. (1982) explained that low fiber recovery from the outer leaf sheaths was probably due to the developed parenchyma cells attached to the fibers and presence of stigmata which made the surface of fibre rough causing more friction during stripping. Moreover, it was documented during tuxy and stripping activities that the outer leaf sheaths were always shorter than those in the inner leaf sheaths which offered difficulty in winding tuxies around the spindle that caused lower fiber recovery. As a general practice in Leyte (Eastern part of the Philippines), a leaf sheath's length less than 1.5 meters is not suitable for machine stripping because of lighter weight of tuxies stripped per unit of time that results in lower fiber recovery per unit cost (i.e., gasoline and labor).

The fiber quality (i.e., tensile strength, fineness, color) was not negatively affected by any of the experimental parameters applied except for fiber length which was strongly correlated (r=0.98) to leaf sheath's length. Fibers from the outer leaf sheaths were stronger than those from inner leaf sheaths. This may be due to the physiological age which varies among the leaf sheaths in the pseudostem or stalk. Inner leaf sheaths are always physiologically younger than the outer regardless of the age of the plant. Alemania et al. (1982) revealed that fiber tensile strength decreases as tuxies are extracted from the leaf sheath nearer to the core of the stalk. The significant effects of shade, irrigation and fertilizer application on fiber fineness and tensile strength of abaca fiber strands were directly determined on the position of the strand in the stalks. This could be attributed to the structural development stages of the fibers, fibers bundles during the growth, and perhaps to varying chemical characteristics (Sinon et al., 2011). Jahan et al. (2008) studying on the chemical characteristics of jute's (*Chorcorus capsularis*) bark and core at different positions found a decreasing lignin content and increasing α-cellulose content from base to top. Sinon et al. (2011) explained that lignin content could be related to the adhesion of fibers in the bundle. He added that the length of the individual fibers and thickness of their cell walls could influence the tenacity of the strands, as well as the fineness resulting during stripping.

Meanwhile, it was observed that the outer fiber had darker color compared to inner fiber. Bales et al. (1981) explained that the dark color of the outer fiber was due to high concentration of pigments since these are usually exposed to sunlight. Usually, dark brown fibers with good cleaning are classified as H/S-H grade (soft brown) or with fair cleaning are classified as JK/S-JK grade (Sievert, 2009). The prices per kilo of these fiber grades are usually much lower than the white fiber (usually S2/S-S2 grades). In this study, the fibers extracted from the inner leaf sheaths were classified as S2/S-S2 grade (streaky) while outer leaf sheaths fibers were classified H/S-H grade (soft brown). The outer or dark fibers are usually stronger and suitable for cordage while the inner or white fibers are weaker and often used in textile industry (Halos, 2008).

Finally, the fiber yield presented in this paper was based on the data collected from the first harvest using portable stripping machine wherein the peak of production has not been reached. The peak of abaca production is usually attained usually four years (Alcober, 1986) to eight years (Sievert, 2009) after planting. Thus, it is highly advised that in using and comparing the data presented in this paper to other published documents in calculating yield plant^{-1} to predict yield hectare^{-1}, appropriate consideration on the following production and processing factors should be taken into account: a) planting density hectare^{-1}, b) number of stalk harvested hectare^{-1}, c) frequency of harvest year^{-1}, d) method of fiber stripping used, e) age of production, and f) crop variety. Hence, this will minimize the risk of either overestimating or underestimating the calculated yield over actual fiber yield.

3.5 Conclusions

The study was carried out to determine the influence of different light intensities, nutrient and water supply on fiber yield and quality of abaca. This will connect the knowledge gap on what is the optimum light requirement of abaca needed to achieve the optimum yield without affecting the quality of the fiber for industrial purposes. Based on the results of the study, it is concluded that the increase in light intensity, water and nutrient supply has no negative effect on fiber quality of the stripped fiber but has significant impact on the physiological performance of the plant that influenced fiber recovery and yield of the crop.

Therefore, it is further concluded that the optimum light to attain an optimum yield without jeopardizing fiber quality was 50% shade. However, if the crop is grown at this level of shade, proper horticultural management (i.e., fertilizer application) has to be implemented to optimize its supply of nutrients as supported by the significant effects of fertilizer application on abaca growth in this study. This was further substantiated by the two-factor interaction effect of shade and irrigation-fertilizer application treatments on outer leaf sheaths, inner leaf sheath, and total fiber yields.

3.6 Acknowledgement

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4. Biomass production and nutrient absorption among abaca plant organs as influenced by different shade conditions, water and nutrient management

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OUTLINE AND OVERVIEW

This section illustrates the influence of different shade conditions, water and nutrient management on biomass production and allocation as well as on NPK absorption and distribution in all abaca organs from seedling to flagleaf stages of crop growth. This chapter shows a broad representation on the pattern of biomass allocation and NPK distribution among abaca organs as influenced by reducing irradiance, water and nutrient availability. It also discusses the morphological acclimations of abaca and NPK resorption or retranslocation to subsequent generations of suckers during leaf senescence.

Biomass Production and Nutrient Absorption among Abaca Plant Organs as Influenced by Different Shade Conditions, Water and Nutrient Management

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ABSTRACT

Abaca (*Musa textilis*), being a shade tolerant and shallow rooted plant, is able to exploit a limited zone of soil. A careful evaluation of its nutrient absorption in relation to biomass production is needed, particularly under different shade and soil conditions. This study was performed to investigate the effect of shade and irrigation-fertilization on biomass production and allocation as well as on NPK absorption and distribution among abaca organs. The study also aimed to examine if irrigation and fertilization could offset the effect of shade on biomass production and NPK absorption in all abaca plant parts. The design of the experiment was a 4x4 factorial combination of shade and irrigation-fertilizer application. Light infiltration was reduced by 30%, 40%, and 50% of full sunlight using polypropylene shade nets. Irrigation was supplied at a rate of 5 liters plant^{-1} application^{-1} day^{-1} while fertilizer was applied at a recommended rate of 43 kg of N, P_2O_5, and K_2O hectare^{-1}. Results showed that shade considerably improved biomass production ($p \leq 0.01$) which significantly enhanced ($p \leq 0.05$) dry matter allocation among abaca organs. The amount of NPK absorbed by each organ was influenced by the growth made during the different stages of crop development. Biomass production and distribution was significantly affected by high radiation (temperature) at seedling and early vegetative stages, and differential leaf senescence at flagleaf stage. Irrigation and fertilizer application further improved biomass production and allocation that considerably increased ($p \leq 0.05$) NPK absorption and distribution among plant parts. Therefore, the positive effect of shade on biomass production and NPK absorption was due to the fact that the detrimental effect of photoinhibition and/or photooxidative damage on abaca at seedling and early vegetative stages (if grown under full sunlight) was avoided and cannot be neutralized by irrigation and fertilizer application.

Keywords: Biomass allocation, nutrient distribution, irrigation, fertilization, shading effect, fiber crop, *Musa textilis*

4.1 Introduction

Abaca is closely related to edible banana (*Musa acuminata* and *Musa balbisiana*) and is grown primarily for its fibers (Armecin, 2008; Halos, 2008; Sievert, 2009). Abaca thrives well in the shade beneath tall trees, and is especially important for protecting the young plants from the sun and the older, taller plants from wind breakage. Abaca plants can be propagated by seeds or by vegetative cloning (i.e., sucker, corm or seed pieces, tissue culture). It takes 18-24 months in fertile forestland and 24-30 months in open places with continuous cropping before abaca can be harvested (Halos, 2008). The peak of abaca production is usually attained from four years (Alcober, 1986) to eight years (Sievert, 2009) after planting and its productivity can last for 20 years (Gonzal et al., 2003). Generally, abaca-based agroecosystems in the Philippines are concentrated in mountainous areas (Armecin and Gabon, 2008) and farmers do not apply fertilizer to their plants (Lacuna-Richman, 2002).

Nutrition is among the many factors affecting the growth and development of abaca plants and has the most appreciable influence on the production of good quality fiber (Sinon, 2008). The allocation of nutrients within the plant is of interest, as it determines the amounts which may be removed from the farm, returned to the soil in dead plant part, available for re-translocation to subsequent generations of suckers (Turner and Lahav, 1986). Abaca fresh biomass has been found to range from 0.8 to 33.2 tons ha^{-1} (Armecin et al., 2011) where 2% of the total biomass is removed from the production area during harvest in the form of fiber (Sinon, 2008). Halos (2008) reported that in every 100 tons of fresh abaca biomass, these contain 280 kg N, 30 kg P, and 517 kg K which could be considered as potential risk of nutrient depletion if these will be removed from the farm. Furthermore, this would lead to the depletion of the nutrient reserve in the soil that would cause significant reduction of the fiber yield if not properly managed and understood.

In integrating abaca into agroforestry systems, one has to consider radiation interception and the efficiency with which radiation energy is used to produce photosynthates, since this plays a crucial role in the growth of tree-crop stands under multi-strata agroecosystem (Balster and Marshall, 2000; Will et al., 2001; Allen et al., 2004; Kemanian et al., 2004). Normally, shading reduces photosynthesis, transpiration and partitioning of biomass from vegetative parts to economic parts (e.g. Akhter et al., 2009). Likewise, if shading is viewed as a way to cool the leaves and to reduce the vapor pressure deficit, differences in surface air temperature among shaded abaca plants with reference to abaca grown in full sunlight is another factor that might affect photosynthetic productivity (Raveh et al., 2003). Turner and Lahav (1986) studying edible banana (AAA group and Cavendish sub-group) found that temperature influences the distribution of dry matter between above and belowground plant organs. On the other hand, Moorby (1981) documented long-term effects of temperature on nutrient distribution within plants that are usually exerted through changes in the patterns of growth within the different plant organs.

Several studies revealed that low nitrogen (N), phosphorus (P), and potassium (K) nutrition in plants could lead to lower photosynthetic rates and slower leaf expansion rate (Evans, 1983; Field and Mooney, 1986; Gerik et al., 1998; Zhao et al., 2003). Robinson and Alberts (1986) reported that growth rate, stem girth and yield of *Musa* were substantially reduced and stress symptoms became evident when available moisture dropped below 66% of field capacity. To date information on how light and water availability affects dry matter allocation and nutrient distribution on abaca organs under field conditions is limited, although much has been known on the plant’s responses to fertilizer application. It would be of great interest to study and analyze the biomass allocation and nutrient absorption by different abaca plant parts since these would give an idea of NPK distribution in the whole plant under different shade conditions, water and nutrient management. Hence, this study was performed to investigate the effect of shade and irrigation-fertilization on biomass production and allocation as well as on NPK absorption and distribution among abaca organs. Likewise, the study aimed to determine if irrigation and fertilization could offset the effect of shade on biomass production and NPK absorption in all abaca plant parts.

4.2 Materials and methods

4.2.1 Location, soil and climatic condition of the study site

The study site was established in an abaca farmer's area in Barangay Catmon, Ormoc City, Philippines located at 11^o 04′ 52.4″ N and 124^o 34′ 29.5″ E on an alluvial terrace with an elevation of 44.5 meters above mean sea level and a slope of 0-3%. The site has an average annual precipitation of 2600 mm yr^{-1} and a mean annual temperature of 27.5 ^oC. The site had been previously planted with sugarcane (*Saccharum officinarum*) and then left under fallow for ten years. Constant grazing caused the grasses to dominate the vegetation structure of the site. The soil is classified as a Haplic Alisol (IUSS Working Group WRB, 2006), whose clay fraction is dominated by kaolinite and haloysite (Asio, 1996). The soil has more than 60% P retention capacity and contains significant amounts of goethite and hematite (Asio et al., 1998).

The pH values for the 0-30 cm and 30-60 cm soil depths were 5.16±0.39 and 5.14±0.04, respectively, indicating strong acidic conditions (Soil Conservation Society of America, 1982). Bulk density ranged from 1.05±0.01 g cm^{-3} to 1.12±0.01 g cm^{-3} with very minor variations in the values indicating high porosity of the soil. Furthermore, results revealed that there were no significant differences in the total N (ranged from 1.05±0.04 to 1.53±0.03 g kg^{-1}) between different treatments and soil depths. Available P was much higher in the top soil (30.67±2.72 mg kg^{-1}) than in the sub-surface soil (4.17±0.97 mg kg^{-1}). On the other hand, exchangeable K was generally much lower in the surface (0.52±0.04 $cmol_c$ kg^{-1}) than in the sub-surface horizon (0.55±0.04 $cmol_c$ kg^{-1}).

4.2.2 Experimental design

The design of the experiment was a 4x4 factorial combination of shade and irrigation-fertilizer application. Tissue cultured abaca seedlings (var. *Laylay*) were planted in a split-plot randomized block design with four replications. The dimension of each main plot (shade) was 30m x 30m. Since there were four sub-plots, a total of 64 plots were established with a dimension of 12.5m x12.5m $plot^{-1}$. The planting distance was 2.5 m x 2.5 m (square method).

4.2.3 Shade and drip irrigation installation and application

Three different shade nets made of polypropylene (Bayview Fishing Supply and General Merchandise, Manila, Philippines) were used: B-double (4mm x 5mm mesh size), A-double (3.5mm x 2.5mm mesh size) and dry nets (2mm x 2mm mesh size) that permitted 70%, 60%, and 50% of full sunlight, respectively. The nets were installed at an initial height of 3.7 meters and were raised to 6.0 meters seven months after planting (MAP).

A drip irrigation system was improvised by installing 288 20-liter water containers in sub-plots. One container was properly leveled and installed at the center of four abaca plants to attain uniform distribution of water among plants at a rate of 5 liters per plant per application. Since there was no available information on the evaporative demand of the crop, irrigation was applied during the dry period when soil moisture was below 26% as determined using gravimetric method. Irrigation was applied two times at seedling stage (1-3 MAP), three times at the early vegetative stage (4-6 MAP), four times at the late vegetative stage (7-9 MAP), and five times at flagleaf stage (10-12 MAP).

4.2.4 Fertilizer application and crop management

A fertilizer recommended rate of 43 kg N, P_2O_5 and K_2O per hectare for each of the fertilized plots using complete (14-14-14) fertilizer was used. This was applied in five different periods of crop growth. At planting, a blanket application of 5 grams per plant was done. At three and six months after planting, a placement application of 10 grams per plant was applied. This was increased to 28 grams per plant at nine and twelve months after planting. During the conduct of the study, there was no available and published data on the critical nutritional level of abaca plants; hence, the National Abaca Research Center and Fiber Development Authority recommendations were used.

Monthly weeding was done when the surrounding vegetation of the plantation threatened to interfere with the growth of the abaca plants. Suckers were pruned bimonthly starting one MAP until six MAP to control overproduction which could eventually affect the physiological performance of the mother (sample) plant.

4.2.5 Destructive harvesting and preparation of plant tissue samples

Destructive harvesting was conducted at the seedling, early vegetative, late vegetative and flagleaf stages of growth of the sample plants (excluding border plants). Four sample plants per treatment per replication were excavated. Biomass samples were separated into plant organs (i.e., roots, corm, leaf sheath or pseudo stem, leaf stalks, leaves) and fresh weight was determined for each plant organ. Tissue samples were collected per organ and were decontaminated with tap water to remove all soil particles and other extraneous materials and finally washed with distilled water. Samples were oven-dried at 60 ^{0}C for 24 hours or until constant dry weight was reached.

The proportional allocation of dry matter among abaca organs was calculated using the following formulas (Turner and Lahav, 1986; Lamber et al., 1998):

$$\text{Dry Biomass}_{\text{Proportional Allocation}} = \frac{D_o}{D_w} \qquad (1)$$

Where: D_o = the mass of dry matter in an organ (g)
D_w = the mass of dry matter in the whole plant (g)

4.2.6 Preparation of ash solution and determination of NPK concentrations

The dried samples were ground in a Wiley mill into a particle size of less than 1 mm (20 mesh screen). One gram of thoroughly mixed ground tissue samples of different plant organs were incinerated in a muffle furnace for about 8 hours at 550 °C temperature. Ash samples were dissolved in a 1.0 N hydrochloric acid solution and filtered through a Whatman #42 filter paper into a volumetric flask. The ash solutions produced per plant organ were used to quantify K using an atomic absorption spectrophotometer. P concentration was determined colorimetrically using ascorbic acid as reducing reagent. This was done at the Central Analytical Services Laboratory, PhilRootcrops Complex, Visayas State University. On the other hand, a 0.2 gram of thoroughly mixed ground tissue samples of different plant organs was prepared for total N determination. These were digested and quantified using a micro-Kjeldahl distilling apparatus at the Soil Research Testing and Plant Analysis Laboratory, Department of Agronomy and Soil Science, Visayas State University.The nutrient (i.e., NPK) absorption and proportional distribution among abaca organs were calculated using the following formulas (Turner and Lahav, 1986; Lahav and Turner, 1985)

$$\text{Nutrient}_{\text{Absorption}} = (R_w)(C_m) \qquad (2)$$

$$\text{Nutrient}_{\text{Proportional distribution}} = \frac{M_o}{M_w} \times 100 \qquad (3)$$

Where: R_w = relative growth of an organ (g)
C_m = concentration of nutrient in an organ
M_o = the mass of nutrient, M, in an organ (g)
M_w = the mass of nutrient, M, in the whole plant (g)

4.2.7 Statistical analyses

All data were tested for normality and homogeneity using PROC Univariate of Statistical Analysis System version 9.1(SAS, 2003). PROC GLM (general linear model) procedure was initially performed to check for effects of shading, irrigation, fertilizer application and their interactions on abaca biomass and nutrient partitioning. The final models for each response variable were analyzed; however, only those significant main factors and two-factor interaction effects for each stage of growth were included. Duncan multiple range test (DMRT) and least squares differences (LSDs) were carried out to compare treatment means of independent variables with significant variations at <0.05 probability.

4.3 Results

4.3.1 Biomass production among plant organs

The study revealed a significant effect ($p \leq 0.01$) of shade on abaca's biomass production among plant organs. Table 4.1 shows that shade considerably increased the leaves dry matter (DM), leafstalks DM, pseudostem DM, corm DM and roots DM. The abaca planted under 50% shade had significantly ($p \leq 0.01$) higher growth rate ($g_{\text{dry matter}}\ d^{-1}$) compared to 0% shade. This was because the abaca grown in 0% shade was negatively affected by high radiation (temperature) where most of the leaves got sunburned (photooxidative damage). The burning led to the reduction on the number of leaves per plant which reduced cumulative leaf area and ultimately affected net assimilation rate (photoinhibition) during the seedling stage.

Statistical analysis showed that shade constantly and positively affected crop growth rate (CGR) from seedling to flagleaf stage. The lowest crop CGR was documented during the seedling stage while the highest was recorded at late vegetative stage. However, this tends to decline at flagleaf stage because the plant was close to its maturity, switching from vegetative to generative growth stage.

The abaca plants treated with NPK fertilizer had accumulated higher biomass in all plant organs from seedling stage to flagleaf stage (Table 4.2). Supplemental irrigation had no significant effect on dry matter production which probably suggests that the incidental rainfall during the period of the experiment was sufficient for plant growth and development. The result could be different during long drought periods due to El Niño or climate change.

Furthermore, CGR was consistently and positively affected ($p \leq 0.05$) by fertilizer application and/or combination of irrigation and fertilizer application. The CGR considerably increased on the abaca plants treated with NPK fertilizer and/or combination of irrigation-fertilization compared to plants supplied only with irrigation and/or without irrigation and fertilization. Likewise, the high net assimilation rate at the seedling stage shows that adequate NPK supply was critical at this particular period of crop growth.

Table 4.1 Dry matter production (g plant^{-1}) among abaca organs at different developmental stages as affected by shade across irrigation and fertilization treatments

Plant Organs	Shade Treatments	Stages of Plant Growth			
		Seedling	Early vegetative	Late vegetative	Flagleaf
Leaves	0% shade	28.9±7.4^{b}	54.1±15.5^{b}	168.5±31.9^{b}	159.3±26.2^{c}
	30% shade	50.2±7.4^{ab}	120.7±15.5^{a}	218.8±31.9^{b}	182.9±26.2^{c}
	40% shade	49.1±7.4^{ab}	128.8±15.5^{a}	202.5±31.9^{b}	313.6±26.2^{b}
	50% shade	61.8±7.4^{a}	133.8±15.5^{a}	312.8±31.9^{a}	440.2±26.2^{a}
Leaf stalks	0% shade	8.0±2.0^{c}	18.8±5.9^{b}	64.3±12.8^{b}	63.3±11.4^{c}
	30% shade	14.5±2.0^{ab}	43.7±5.9^{a}	84.1±12.8^{b}	82.5±11.4^{bc}
	40% shade	13.2±2.0^{bc}	45.0±5.9^{a}	78.2±12.8^{b}	104.7±11.4^{b}
	50% shade	20.1±2.0^{a}	43.1±5.9^{a}	122.3±12.8^{a}	162.6±11.4^{a}
Pseudostem	0% shade	30.4±8.1^{b}	88.6±19.5^{b}	282.9±53.1^{b}	422.3±57.2^{b}
	30% shade	60.6±8.1^{a}	160.8±19.5^{a}	371.1±53.1^{ab}	530.2±57.2^{ab}
	40% shade	55.4±8.1^{a}	160.5±19.5^{a}	342.8±53.1^{b}	540.5±57.2^{ab}
	50% shade	76.2±8.1^{a}	197.5±19.5^{a}	502.2±53.1^{a}	656.6±57.2^{a}
Corm	0% shade	21.7±6.3^{b}	47.4±10.6^{b}	130.2±17.7^{b}	206.2±22.9^{c}
	30% shade	41.7±6.3^{a}	95.6±10.6^{a}	155.8±17.7^{b}	225.7±22.9^{bc}
	40% shade	37.6±6.3^{ab}	101.0±10.6^{a}	149.1±17.7^{b}	287.2±22.9^{ab}
	50% shade	45.8±6.3^{a}	102.4±10.6^{a}	214.3±17.7^{a}	305.7±22.9^{a}
Roots	0% shade	23.0±5.3^{b}	33.3±8.7^{c}	89.0±14.2^{b}	148.4±17.2^{b}
	30% shade	36.7±5.3^{ab}	63.3±8.7^{b}	106.2±14.2^{b}	157.8±17.2^{b}
	40% shade	36.9±5.3^{ab}	85.1±8.7^{ab}	127.7±14.2^{ab}	215.9±17.2^{a}
	50% shade	48.7±5.3^{a}	96.7±8.7^{a}	149.1±14.2^{a}	235.2±17.2^{a}

Note: least square means in each cell within the column of a specific stage of plant growth with different letter superscripts (a-c) are significantly different at $p<0.05$, n=16

Table 4.2 Dry matter production (g plant^{-1}) among abaca organs at different developmental stages as affected by irrigation (I) and fertilization (F) across shade treatments

Plant Organs	Irrigation and Fertilizer Treatments	Stages of Plant Growth			
		Seedling	Early vegetative	Late vegetative	Flagleaf
Leaves	Without I and F	33.0±7.4^{b}	78.6±15.5^{c}	143.6±31.9^{c}	204.4±26.2^{b}
	Without I, with F	53.0±7.4^{ab}	129.2±15.5^{ab}	301.9±31.9^{a}	294.1±26.2^{a}
	With I, without F	42.7±7.4^{ab}	89.8±15.5^{bc}	203.8±31.9^{bc}	288.2±26.2^{a}
	With I and F	61.3±7.4^{a}	139.6±15.5^{a}	253.2±31.9^{ab}	309.3±26.2^{a}
Leaf stalks	Without I and F	10.2±2.0^{b}	26.9±5.9^{c}	53.4±12.8^{c}	73.1±11.4^{b}
	Without I, with F	15.7±2.0^{ab}	45.0±5.9^{ab}	119.2±12.8^{a}	110.7±11.4^{a}
	With I, without F	12.0±2.0^{ab}	30.5±5.9^{bc}	78.4±12.8^{bc}	102.8±11.4^{ab}
	With I and F	17.8±2.0^{a}	48.2±5.9^{a}	97.9±12.8^{ab}	126.5±11.4^{a}
Pseudostem	Without I and F	40.0±8.1^{b}	100.3±19.5^{b}	213.7±53.1^{b}	388.0±57.2^{c}
	Without I, with F	66.1±8.1^{a}	200.7±19.5^{a}	510.6±53.1^{a}	621.0±57.2^{ab}
	With I, without F	48.9±8.1^{ab}	109.4±19.5^{b}	305.1±53.1^{b}	479.7±57.2^{bc}
	With I and F	67.6±8.1^{a}	197.1±19.5^{a}	469.5±53.1^{a}	661.3±57.2^{a}
Corm	Without I and F	26.2±6.3^{a}	60.2±10.6^{b}	121.6±17.7^{b}	220.4±22.9^{a}
	Without I, with F	42.1±6.3^{a}	106.7±10.6^{a}	203.2±17.7^{a}	280.8±22.9^{a}
	With I, without F	30.7±6.3^{a}	77.3±10.6^{ab}	150.3±17.7^{ab}	228.2±22.9^{a}
	With I and F	48.0±6.3^{a}	102.2±10.6^{a}	174.2±17.7^{ab}	295.4±22.9^{a}
Roots	Without I and F	25.7±5.3^{a}	52.2±8.7^{b}	88.9±14.2^{b}	162.4±17.2^{a}
	Without I, with F	40.3±5.3^{a}	83.5±8.7^{a}	145.4±14.2^{a}	202.2±17.2^{a}
	With I, without F	34.2±5.3^{a}	57.8±8.7^{b}	105.1±14.2^{ab}	180.8±17.2^{a}
	With I and F	45.1±5.3^{a}	84.8±8.7^{a}	132.6±14.2^{a}	212.0±17.2^{a}

Note: least square means in each cell within the column of a specific stage of plant growth with different letter superscripts (a-c) are significantly different at $p<0.05$, n=16

4.3.2 Biomass allocation among plant organs

The effects of shade on biomass partitioning among abaca organs are shown in Table 4.3. Statistical analysis revealed that shade significantly affected biomass allocation in both leaves and pseudostem at the early vegetative stage ($p \leq 0.05$) and flagleaf stage ($p \leq 0.01$), respectively. Leaf mass ratio was higher at seedling stage but tend to decline at late vegetative stage until flagleaf stage.

A continuous increase in pseudostem mass ratio was recorded starting from early vegetative until flagleaf stage. Meanwhile, root mass ratio ($p=0.0286$) was considerably affected at late vegetative stage. However, shade had no significant influence on corm mass ratio during the entire developmental stage of crop growth.

Table 4.3 Proportional allocation of dry biomass among abaca organs at different stages of plant growth as affected by shade across irrigation and fertilizer application treatments

Parameters	Shade Treatments	Stages of Plant Growth			
		Seedling	Early vegetative	Late vegetative	Flagleaf
Leaf Mass Ratio (g g^{-1})	0% shade	0.327±0.013^{a}	0.272±0.012^{b}	0.304±0.009^{a}	0.217±0.009^{c}
	30% shade	0.314±0.013^{a}	0.326±0.012^{a}	0.317±0.009^{a}	0.215±0.009^{c}
	40% shade	0.321±0.013^{a}	0.326±0.012^{a}	0.314±0.009^{a}	0.286±0.009^{b}
	50% shade	0.322±0.013^{a}	0.308±0.012^{a}	0.327±0.009^{a}	0.331±0.009^{a}
Pseudostem Mass Ratio (g g^{-1})	0% shade	0.251±0.013^{b}	0.328±0.012^{ab}	0.363±0.013^{a}	0.409±0.014^{a}
	30% shade	0.290±0.013^{a}	0.323±0.012^{ab}	0.366±0.013^{a}	0.429±0.014^{a}
	40% shade	0.292±0.013^{a}	0.299±0.012^{b}	0.365±0.013^{a}	0.365±0.014^{b}
	50% shade	0.306±0.013^{a}	0.348±0.012^{a}	0.384±0.013^{a}	0.362±0.014^{b}
Corm Mass Ratio (g g^{-1})	0% shade	0.213±0.013^{a}	0.208±0.009^{a}	0.199±0.012^{a}	0.218±0.012^{a}
	30% shade	0.201±0.013^{a}	0.207±0.009^{a}	0.191±0.012^{a}	0.209±0.012^{a}
	40% shade	0.191±0.013^{a}	0.202±0.009^{a}	0.172±0.012^{a}	0.198±0.012^{a}
	50% shade	0.177±0.013^{a}	0.178±0.009^{a}	0.172±0.012^{a}	0.175±0.012^{a}
Root Mass Ratio (g g^{-1})	0% shade	0.209±0.009^{a}	0.172±0.012^{a}	0.135±0.008^{ab}	0.155±0.007^{a}
	30% shade	0.194±0.009^{a}	0.144±0.012^{a}	0.126±0.008^{b}	0.147±0.007^{a}
	40% shade	0.195±0.009^{a}	0.173±0.012^{a}	0.149±0.008^{a}	0.151±0.007^{a}
	50% shade	0.195±0.009^{a}	0.166±0.012^{a}	0.117±0.008^{b}	0.131±0.007^{a}

***Note*:** least squares means in each column within the cell with different letter superscripts (a-c) are significantly different at $p<0.05$, $n=16$

Irrigation and fertilizer application significantly influenced ($p \leq 0.05$) biomass allocation among abaca organs (Table 4.4). Statistical analysis showed that the effect of irrigation-fertilization on biomass distribution significantly differed as the plant started to develop from seedling to flagleaf stage. The influence of irrigation-fertilization treatments on biomass partitioning among organs was noticeable at vegetative stages of crop growth.

Furthermore, analysis of variance results showed that the effect of shade and irrigation-fertilization treatments on the pattern of biomass partitioning among abaca organs was clear at early vegetative stage. A shift of higher biomass allocation towards the pseudostem started at early vegetative stage in 0% and 50% shade. A similar trend was observed on abaca plants treated with NPK fertilizer and/or a combination of irrigation and fertilizer application.

Table 4.4 Proportional allocation of dry biomass among abaca organs at different stages of plant growth as affected by irrigation (I) and fertilizer (F) application across shade treatments

Parameters	Irrigation and Fertilizer Treatments	Stages of Plant Growth			
		Seedling	Early vegetative	Late vegetative	Flagleaf
Leaf Mass Ratio (g g^{-1})	Without I and F	0.315±0.013^{a}	0.321±0.012^{a}	0.313±0.009^{a}	0.246±0.009^{b}
	Without I, with F	0.320±0.013^{a}	0.308±0.012^{a}	0.325±0.009^{a}	0.259±0.009^{ab}
	With I, without F	0.319±0.013^{a}	0.302±0.012^{a}	0.316±0.009^{a}	0.283±0.009^{a}
	With I and F	0.330±0.013^{a}	0.322±0.012^{a}	0.308±0.009^{a}	0.262±0.009^{ab}
Pseudostem Mass Ratio (g g^{-1})	Without I and F	0.278±0.013^{a}	0.310±0.012^{ab}	0.345±0.013^{b}	0.371±0.014^{b}
	Without I, with F	0.300±0.013^{a}	0.344±0.012^{a}	0.384±0.013^{a}	0.404±0.014^{ab}
	With I, without F	0.283±0.013^{a}	0.301±0.012^{b}	0.341±0.013^{b}	0.370±0.014^{b}
	With I and F	0.279±0.013^{a}	0.342±0.012^{a}	0.409±0.013^{a}	0.420±0.014^{a}
Corm Mass Ratio (g g^{-1})	Without I and F	0.209±0.013^{a}	0.200±0.009^{ab}	0.193±0.012^{a}	0.216±0.012^{a}
	Without I, with F	0.191±0.013^{a}	0.193±0.009^{ab}	0.174±0.012^{a}	0.198±0.012^{a}
	With I, without F	0.184±0.013^{a}	0.219±0.009^{a}	0.204±0.012^{a}	0.201±0.012^{a}
	With I and F	0.197±0.013^{a}	0.182±0.009^{b}	0.162±0.012^{b}	0.185±0.012^{a}
Root Mass Ratio (g g^{-1})	Without I and F	0.196±0.009^{a}	0.169±0.012^{a}	0.149±0.008^{a}	0.167±0.007^{a}
	Without I, with F	0.189±0.009^{a}	0.155±0.012^{a}	0.117±0.008^{c}	0.139±0.007^{b}
	With I, without F	0.214±0.009^{a}	0.178±0.012^{a}	0.139±0.008^{ab}	0.146±0.007^{b}
	With I and F	0.193±0.009^{a}	0.154±0.012^{a}	0.121±0.008^{bc}	0.132±0.007^{b}

Note**:** least squares means in each column within the cell with different letter superscripts (a-c) are significantly different at $p<0.05$, n=16

4.3.3 N absorption and distribution among plant organs

Table 4.5 shows that shade significantly influenced N absorption ($p \leq 0.01$) and distribution ($p \leq 0.05$) among abaca organs. The amount of N absorbed was influenced by the amount of growth made (i.e., dry biomass) by each respective organ. As presented in Table 4.1, dry matter production among plant organs was significantly affected by radiation. The effect was apparent on the leaves where leaf mass ratio was considerably reduced (Table 4.3). This significantly affected the amount of N absorbed (by the leaves) on the abaca plants grown in full sunlight compared to the shaded treatments during the seedling ($p=0.0091$) and early vegetative ($p=0.0496$) stages of crop growth. Furthermore, statistical analysis showed that N uptake by leaves and leafstalks had increased from seedling stage to late vegetative stage and declined at flagleaf stage. In contrast, N uptake by pseudostem, corm and roots consistently increased from seedling until flagleaf stages of plant growth. This implies that resorption or retranslocation of N to subsequent generations of suckers was more apparent during leaf senescence and most particularly on abaca grown in 0% and 30% shade.

On the other hand, the amount of N distributed to different abaca organs varied significantly with shade treatment and developmental stages of the crop. The effect was evident on abaca plants grown in 0% shade during the late vegetative stage of crop growth. This totally changed the pattern of N distribution to the different organs of abaca grown under full sunlight (in the order leaves>pseudostem>corm>roots>leafstalks) compared to the shaded treatments (in the order leaves>pseudostem>roots>corm>leafstalks). Independent of the effects of shade, leaves consistently received higher share of N compared to other plant organs from seedling until late vegetative stage. But, this considerably declined at flagleaf stage.

NPK fertilization and/or combination of irrigation and fertilizer application enhanced biomass production of abaca at different stages of crop growth (Table 4.2). This considerably improved N absorption ($p \leq 0.05$) and significantly influenced N distribution ($p \leq 0.01$) to the different abaca organs (Table 4.6). However, the increase in N absorption did not alter the normal pattern of N distribution. Supplemental irrigation had no effect on N uptake, but had significant influence on N distribution among plant organs.

Table 4.5 N absorption (g plant^{-1}) and proportional distribution (%) among abaca organs at different developmental stages as affected by shade across irrigation-fertilization treatments

Plant Organs	Shade Treatments	Stages of Plant Growth							
		Seedling		Early vegetative		Late vegetative		Flagleaf	
		Absorption	Distribution	Absorption	Distribution	Absorption	Distribution	Absorption	Distribution
Leaves	0% shade	47.2 ± 18.4^{b}	51.3 ± 1.6^{a}	66.3 ± 37.3^{b}	46.0 ± 1.2^{a}	217.5 ± 63.9^{a}	48.8 ± 0.9^{b}	-15.1 ± 45.8^{b}	34.8 ± 1.0^{c}
	30% shade	103.7 ± 18.4^{a}	51.8 ± 1.6^{a}	167.0 ± 37.3^{a}	48.5 ± 1.2^{a}	245.7 ± 63.9^{a}	61.0 ± 0.9^{a}	-69.6 ± 45.8^{b}	35.0 ± 1.0^{c}
	40% shade	88.6 ± 18.4^{ab}	51.1 ± 1.6^{a}	200.0 ± 37.3^{a}	48.9 ± 1.2^{a}	151.6 ± 63.9^{a}	60.9 ± 0.9^{a}	210.1 ± 45.8^{a}	42.3 ± 1.0^{b}
	50% shade	139.7 ± 18.4^{a}	50.7 ± 1.6^{a}	180.1 ± 37.3^{a}	45.8 ± 1.2^{a}	451.9 ± 63.9^{a}	55.7 ± 0.9^{b}	251.0 ± 45.8^{a}	45.3 ± 1.0^{a}
Leaf-stalks	0% shade	3.7 ± 1.5^{c}	4.7 ± 0.3^{a}	11.1 ± 5.1^{b}	5.7 ± 0.2^{c}	26.5 ± 6.4^{b}	5.1 ± 0.1^{a}	-0.8 ± 7.3^{b}	4.8 ± 0.3^{a}
	30% shade	8.6 ± 1.5^{b}	4.4 ± 0.3^{a}	27.4 ± 5.1^{a}	6.6 ± 0.2^{a}	23.0 ± 6.4^{b}	4.7 ± 0.1^{b}	4.5 ± 7.3^{ab}	5.4 ± 0.3^{a}
	40% shade	7.4 ± 1.5^{bc}	4.4 ± 0.3^{a}	30.8 ± 5.1^{a}	6.5 ± 0.2^{ab}	13.5 ± 6.4^{b}	4.4 ± 0.1^{b}	14.6 ± 7.3^{ab}	4.3 ± 0.3^{a}
	50% shade	13.3 ± 1.5^{a}	5.1 ± 0.3^{a}	22.7 ± 5.1^{ab}	5.9 ± 0.2^{bc}	47.1 ± 6.4^{a}	4.8 ± 0.1^{ab}	24.1 ± 7.3^{a}	5.1 ± 0.3^{a}
Pseudo-stem	0% shade	16.9 ± 7.0^{c}	18.0 ± 0.9^{b}	52.0 ± 16.9^{b}	25.7 ± 1.0^{ab}	121.3 ± 23.9^{b}	25.7 ± 0.8^{a}	86.0 ± 27.7^{b}	37.4 ± 1.2^{ab}
	30% shade	38.6 ± 7.0^{ab}	19.1 ± 0.9^{b}	92.0 ± 16.9^{ab}	25.0 ± 1.0^{b}	103.9 ± 23.9^{b}	18.2 ± 0.8^{b}	112.1 ± 27.7^{ab}	38.8 ± 1.2^{a}
	40% shade	33.1 ± 7.0^{ac}	20.1 ± 0.9^{ab}	92.5 ± 16.9^{ab}	21.9 ± 1.0^{c}	82.6 ± 23.9^{b}	18.1 ± 0.8^{b}	174.6 ± 27.7^{a}	34.5 ± 1.2^{b}
	50% shade	58.2 ± 7.0^{a}	22.1 ± 0.9^{a}	122.5 ± 16.9^{a}	28.0 ± 1.0^{a}	196.7 ± 23.9^{a}	23.6 ± 0.8^{a}	150.8 ± 27.7^{ab}	33.9 ± 1.2^{b}
Corm	0% shade	11.8 ± 3.0^{a}	12.3 ± 0.7^{a}	12.8 ± 6.0^{b}	10.8 ± 0.5^{a}	47.7 ± 7.0^{a}	11.9 ± 0.6^{a}	21.5 ± 6.3^{a}	9.8 ± 0.6^{a}
	30% shade	18.3 ± 3.0^{a}	9.2 ± 0.7^{b}	28.4 ± 6.0^{ab}	9.0 ± 0.5^{bc}	19.0 ± 7.0^{b}	7.9 ± 0.6^{b}	23.1 ± 6.3^{a}	8.6 ± 0.6^{a}
	40% shade	14.1 ± 3.0^{a}	8.0 ± 0.7^{bc}	38.9 ± 6.0^{a}	10.3 ± 0.5^{ab}	12.9 ± 7.0^{b}	5.9 ± 0.6^{c}	56.8 ± 6.3^{a}	8.5 ± 0.6^{a}
	50% shade	17.7 ± 3.0^{a}	6.8 ± 0.7^{c}	33.9 ± 6.0^{a}	8.5 ± 0.5^{c}	55.8 ± 7.0^{a}	8.1 ± 0.6^{b}	34.5 ± 6.3^{a}	6.7 ± 0.6^{b}
Roots	0% shade	11.8 ± 5.0^{b}	13.7 ± 0.9^{a}	7.8 ± 7.1^{b}	11.8 ± 1.0^{a}	33.4 ± 8.8^{a}	9.0 ± 0.5^{b}	34.9 ± 8.5^{b}	13.3 ± 0.6^{a}
	30% shade	27.7 ± 5.0^{a}	15.5 ± 0.9^{a}	22.8 ± 7.1^{ab}	10.8 ± 1.0^{a}	23.3 ± 8.8^{a}	8.2 ± 0.5^{b}	35.4 ± 8.5^{b}	12.3 ± 0.6^{a}
	40% shade	27.4 ± 5.0^{a}	16.4 ± 0.9^{a}	42.1 ± 7.1^{a}	12.3 ± 1.0^{a}	23.8 ± 8.8^{a}	10.7 ± 0.5^{a}	57.4 ± 8.5^{a}	10.3 ± 0.6^{b}
	50% shade	40.7 ± 5.0^{a}	15.2 ± 0.9^{a}	43.3 ± 7.1^{a}	11.8 ± 1.0^{a}	37.6 ± 8.8^{a}	7.8 ± 0.5^{b}	60.7 ± 8.5^{a}	9.0 ± 0.6^{b}

***Note*:** least square means in each cell within the column of a specific stage of plant growth with different letter superscripts (a-c) are significantly different at $p<0.05$, n=16

Table 4.6 N absorption (g plant^{-1}) and proportional distribution (%) among abaca organs at different developmental stages as affected by irrigation-fertilization across shade treatments

Plant Organs	Irrigation and Fertilizer Treatments	Stages of Plant Growth							
		Seedling		Early vegetative		Late vegetative		Flagleaf	
		Absorption	Distribution	Absorption	Distribution	Absorption	Distribution	Absorption	Distribution
Leaves	Without I and F	59.3 ± 18.4^{b}	48.9 ± 1.6^{a}	104.2 ± 37.3^{a}	47.0 ± 1.2^{a}	143.4 ± 63.9^{a}	56.2 ± 0.9^{ab}	112.4 ± 45.8^{ab}	36.6 ± 1.0^{b}
	Without I, with F	106.8 ± 18.4^{ab}	50.5 ± 1.6^{a}	194.0 ± 37.3^{a}	47.1 ± 1.2^{a}	382.8 ± 63.9^{a}	53.8 ± 0.9^{b}	-14.6 ± 45.8^{b}	39.1 ± 1.0^{b}
	With I, without F	84.7 ± 18.4^{ab}	53.9 ± 1.6^{a}	108.6 ± 37.3^{a}	44.9 ± 1.2^{a}	266.7 ± 63.9^{a}	58.7 ± 0.9^{a}	166.5 ± 45.8^{a}	43.1 ± 1.0^{a}
	With I and F	128.4 ± 18.4^{a}	51.8 ± 1.6^{a}	206.4 ± 37.3^{a}	50.4 ± 1.2^{a}	273.8 ± 63.9^{a}	57.7 ± 0.9^{a}	112.2 ± 45.8^{ab}	38.5 ± 1.0^{b}
Leaf-stalks	Without I and F	5.9 ± 1.5^{b}	5.1 ± 0.3^{a}	15.7 ± 5.1^{a}	6.4 ± 0.2^{ab}	7.7 ± 6.4^{b}	2.9 ± 0.1^{d}	9.4 ± 7.3^{a}	4.2 ± 0.3^{b}
	Without I, with F	9.3 ± 1.5^{ab}	4.7 ± 0.3^{a}	31.8 ± 5.1^{a}	7.0 ± 0.2^{a}	46.7 ± 6.4^{a}	6.6 ± 0.1^{a}	-4.5 ± 7.3^{a}	4.7 ± 0.3^{b}
	With I, without F	6.6 ± 1.5^{b}	4.0 ± 0.3^{a}	15.8 ± 5.1^{a}	5.4 ± 0.2^{c}	27.7 ± 6.4^{a}	5.1 ± 0.1^{b}	15.6 ± 7.3^{a}	4.9 ± 0.3^{b}
	With I and F	11.2 ± 1.5^{a}	4.8 ± 0.3^{a}	28.6 ± 5.1^{a}	5.9 ± 0.2^{bc}	27.7 ± 6.4^{a}	4.5 ± 0.1^{c}	22.0 ± 7.3^{a}	5.8 ± 0.3^{a}
Pseudo-stem	Without I and F	26.4 ± 7.0^{a}	22.0 ± 0.9^{a}	53.6 ± 16.9^{b}	23.2 ± 1.0^{a}	50.5 ± 23.9^{c}	21.0 ± 0.8^{b}	146.2 ± 27.7^{a}	36.1 ± 1.2^{a}
	Without I, with F	45.0 ± 7.0^{a}	20.9 ± 0.9^{ab}	123.8 ± 16.9^{a}	25.9 ± 1.0^{a}	187.5 ± 23.9^{a}	20.0 ± 0.8^{b}	85.5 ± 27.7^{a}	38.2 ± 1.2^{a}
	With I, without F	29.4 ± 7.0^{a}	18.0 ± 0.9^{c}	61.0 ± 16.9^{b}	26.3 ± 1.0^{a}	105.8 ± 23.9^{bc}	19.2 ± 0.8^{b}	127.0 ± 27.7^{a}	32.1 ± 1.2^{b}
	With I and F	45.9 ± 7.0^{a}	18.5 ± 0.9^{bc}	120.8 ± 16.9^{a}	25.2 ± 1.0^{a}	160.8 ± 23.9^{ab}	24.8 ± 0.8^{a}	164.7 ± 27.7^{a}	38.2 ± 1.2^{a}
Corm	Without I and F	9.8 ± 3.0^{c}	9.2 ± 0.7^{ab}	20.6 ± 6.0^{a}	11.5 ± 0.5^{a}	27.1 ± 7.0^{a}	9.6 ± 0.6^{a}	40.7 ± 6.3^{a}	10.2 ± 0.6^{a}
	Without I, with F	19.2 ± 3.0^{ab}	8.9 ± 0.7^{ab}	37.6 ± 6.0^{a}	9.0 ± 0.5^{bc}	49.8 ± 7.0^{a}	10.0 ± 0.6^{a}	26.0 ± 6.3^{a}	7.7 ± 0.6^{bc}
	With I, without F	11.8 ± 3.0^{bc}	$7.5\pm0.7_{b}$	25.0 ± 6.0^{a}	10.1 ± 0.5^{ab}	29.6 ± 7.0^{a}	7.9 ± 0.6^{b}	27.7 ± 6.3^{a}	8.9 ± 0.6^{ab}
	With I and F	21.1 ± 3.0^{a}	10.7 ± 0.7^{a}	30.9 ± 6.0^{a}	8.0 ± 0.5^{c}	28.9 ± 7.0^{a}	6.2 ± 0.6^{c}	41.5 ± 6.3^{a}	6.8 ± 0.6^{c}
Roots	Without I and F	17.0 ± 5.0^{b}	14.8 ± 0.9^{a}	22.8 ± 7.1^{a}	11.9 ± 1.0^{a}	23.4 ± 8.8^{a}	10.4 ± 0.5^{a}	46.1 ± 8.5^{a}	13.0 ± 0.6^{a}
	Without I, with F	31.7 ± 5.0^{ab}	15.0 ± 0.9^{a}	38.5 ± 7.1^{a}	11.1 ± 1.0^{a}	38.5 ± 8.8^{a}	9.7 ± 0.5^{a}	35.1 ± 8.5^{a}	10.3 ± 0.6^{b}
	With I, without F	24.4 ± 5.0^{ab}	16.7 ± 0.9^{a}	20.2 ± 7.1^{a}	13.3 ± 1.0^{a}	31.4 ± 8.8^{a}	9.0 ± 0.5^{a}	48.3 ± 8.5^{a}	11.0 ± 0.6^{b}
	With I and F	34.5 ± 5.0^{a}	14.2 ± 0.9^{a}	34.5 ± 7.1^{a}	10.6 ± 1.0^{a}	24.8 ± 8.8^{a}	6.7 ± 0.5^{b}	59.0 ± 8.5^{a}	10.7 ± 0.6^{b}

***Note*:** least square means in each cell within the column of a specific stage of plant growth with different letter superscripts (a-d) are significantly different at $p<0.05$, n=16

4.3.4 P absorption and distribution among plant organs

The results of the study showed that reducing light availability through shading positively affected P uptake ($p \leq 0.01$) among abaca organs at different developmental stages of the crop. The P uptake in response to shade showed similar trend to N uptake, where P uptake increased as the plant vegetative stages evolved and declined when the crop shifted from vegetative to generative stage. The negative values of P absorption on the leaves and leafstalks of abaca grown in 0% and 30% shade during the flagleaf stage could be attributed to the differential leaf senescence which could probably have influenced retranslocation of P to the subsequent generations of suckers.

Analysis of variance showed that shade greatly affected ($p \leq 0.01$) the amount of P distributed to abaca organs. However, the effect significantly varied at different developmental stages of the crop. Table 4.7 shows that pseudostem consistently received high amount of P among the plant organs examined. Furthermore, results revealed that the normal trend of P distribution among abaca organs (independently of the effect of shade on the amount of P absorbed) was in the order pseudostem>leaves>leafstalks>corm>roots.

Table 4.7 P absorption (g plant^{-1}) and proportional distribution (%) among abaca organs at different developmental stages as affected by shade across irrigation-fertilization treatments

Plant Organs	Shade Treatments	Stages of Plant Growth							
		Seedling		Early vegetative		Late vegetative		Flagleaf	
		Absorption	Distribution	Absorption	Distribution	Absorption	Distribution	Absorption	Distribution
Leaves	0% shade	4.6±1.9^{b}	36.5±1.3^{a}	6.9±4.0^{b}	27.5±0.9^{b}	28.6±6.7^{a}	32.2±0.9^{b}	-2.7±6.1^{b}	26.1±0.8^{c}
	30% shade	10.6±1.9^{a}	32.5±1.3^{a}	17.1±4.0^{ab}	30.3±0.9^{a}	24.9±6.7^{a}	33.2±0.9^{b}	-8.8±6.1^{b}	21.7±0.8^{d}
	40% shade	10.0±1.9^{a}	33.1±1.3^{a}	23.0±4.0^{a}	31.4±0.9^{a}	19.0±6.7^{a}	34.5±0.9^{b}	28.9±6.1^{a}	29.9±0.8^{b}
	50% shade	13.8±1.9^{a}	31.6±1.3^{a}	21.3±4.0^{a}	29.1±0.9^{ab}	44.6±6.7^{a}	37.5±0.9^{a}	34.4±6.1^{a}	34.5±0.8^{a}
Leaf-stalks	0% shade	1.3±0.5^{c}	11.2±0.6^{a}	3.6±1.6^{b}	10.6±0.4^{ab}	10.2±2.0^{a}	10.7±0.3^{a}	-0.3±2.3^{b}	9.4±0.4^{a}
	30% shade	3.1±0.5^{ab}	9.9±0.6^{a}	7.4±1.6^{a}	10.6±0.4^{ab}	8.4±2.0^{a}	10.7±0.3^{a}	-0.1±2.3^{b}	8.0±0.4^{a}
	40% shade	2.7±0.5^{bc}	9.0±0.6^{a}	9.7±1.6^{a}	11.6±0.4^{a}	6.7±2.0^{a}	11.0±0.3^{a}	6.3±2.3^{ab}	8.5±0.4^{a}
	50% shade	4.3±0.5^{a}	10.1±0.6^{a}	7.1±1.6^{ab}	9.6±0.4^{b}	11.7±2.0^{a}	8.5±0.3^{b}	8.4±2.3^{a}	8.9±0.4^{a}
Pseudo-stem	0% shade	3.9±2.1^{b}	30.8±1.4^{b}	17.6±5.2^{b}	45.7±1.2^{a}	37.1±7.2^{a}	41.7±1.2^{a}	19.6±7.1^{b}	44.4±1.4^{b}
	30% shade	11.8±2.1^{a}	36.8±1.4^{a}	24.7±5.2^{ab}	41.3±1.2^{b}	40.4±7.2^{a}	41.8±1.2^{a}	39.1±7.1^{ab}	55.5±1.4^{a}
	40% shade	11.6±2.1^{a}	39.8±1.4^{a}	32.0±5.2^{ab}	40.4±1.2^{b}	32.9±7.2^{a}	39.6±1.2^{ab}	48.0±7.1^{a}	45.8±1.4^{b}
	50% shade	16.8±2.1^{a}	40.3±1.4^{a}	39.4±5.2^{a}	47.2±1.2^{a}	48.7±7.2^{a}	37.1±1.2^{b}	34.7±7.1^{ab}	44.1±1.4^{b}
Corm	0% shade	1.3±0.6^{b}	11.4±0.7^{a}	2.2±1.0^{b}	8.4±0.5^{bc}	6.7±1.2^{b}	9.1±0.7^{b}	4.7±1.2^{a}	10.4±0.6^{a}
	30% shade	3.4±0.6^{a}	10.6±0.7^{a}	5.4±1.0^{ab}	10.1±0.5^{a}	4.6±1.2^{b}	8.5±0.7^{b}	4.5±1.2^{a}	7.6±0.6^{bc}
	40% shade	2.6±0.6^{ab}	8.4±0.7^{b}	6.1±1.0^{a}	9.1±0.5^{ab}	3.9±1.2^{b}	8.3±0.7^{b}	11.2±1.2^{a}	8.5±0.6^{b}
	50% shade	3.6±0.6^{a}	8.1±0.7^{b}	5.2±1.0^{a}	7.0±0.5^{c}	11.3±1.2^{a}	11.0±0.7^{a}	5.9±1.2^{a}	6.3±0.6^{c}
Roots	0% shade	1.2±0.6^{b}	10.1±0.6^{a}	1.1±0.8^{b}	7.8±0.7^{a}	4.4±0.9^{a}	6.2±0.4^{a}	4.9±1.1^{a}	9.6±0.5^{a}
	30% shade	3.1±0.6^{a}	10.3±0.6^{a}	2.8±0.8^{ab}	7.6±0.7^{a}	3.5±0.9^{a}	5.9±0.4^{a}	4.3±1.1^{a}	7.2±0.5^{b}
	40% shade	2.9±0.6^{a}	9.8±0.6^{a}	4.6±0.8^{a}	7.5±0.7^{a}	2.9±0.9^{a}	6.6±0.4^{a}	8.0±1.1^{a}	7.3±0.5^{b}
	50% shade	4.3±0.6^{a}	9.9±0.6^{a}	4.9±0.8^{a}	7.2±0.7^{a}	4.0±0.9^{a}	5.8±0.4^{a}	7.6±1.1^{a}	6.2±0.5^{b}

***Note*:** least square means in each cell within the column of a specific stage of plant growth with different letter superscripts (a-d) are significantly different at $p<0.05$, n=16

Table 4.8 shows that NPK fertilization and/or combination of irrigation and fertilizer application drastically enhanced ($p \leq 0.05$) P absorption and significantly influenced ($p \leq 0.01$) P distribution. However, the effect on P absorption was noticeable only on the aboveground plant organs. As expected, P absorption was high on abaca plants treated with NPK fertilizer. The effect of shade on P distribution started at the early vegetative stage until the flagleaf stage of plant growth.

Table 4.8 P absorption (g plant^{-1}) and proportional distribution (%) among abaca organs at different developmental stages as affected by irrigation-fertilization across shade treatments

Plant Organs	Irrigation and Fertilizer Treatments	Stages of Plant Growth							
		Seedling		Early vegetative		Late vegetative		Flagleaf	
		Absorption	Distribution	Absorption	Distribution	Absorption	Distribution	Absorption	Distribution
Leaves	Without I and F	6.2 ± 1.9^{b}	30.7 ± 1.3^{a}	13.0 ± 4.0^{a}	31.0 ± 0.9^{a}	15.8 ± 6.7^{b}	33.8 ± 0.9^{a}	16.1 ± 6.1^{ab}	27.2 ± 0.8^{bc}
	Without I, with F	11.0 ± 1.9^{a}	35.2 ± 1.3^{a}	21.2 ± 4.0^{a}	30.4 ± 0.9^{a}	43.3 ± 6.7^{a}	35.6 ± 0.9^{a}	-1.5 ± 6.1^{b}	31.1 ± 0.8^{a}
	With I, without F	8.6 ± 1.9^{a}	33.4 ± 1.3^{a}	12.2 ± 4.0^{a}	26.6 ± 0.9^{b}	29.3 ± 6.7^{ab}	34.8 ± 0.9^{a}	22.1 ± 6.1^{a}	28.3 ± 0.8^{b}
	With I and F	13.2 ± 1.9^{a}	34.3 ± 1.3^{a}	22.0 ± 4.0^{a}	30.3 ± 0.9^{a}	28.6 ± 6.7^{ab}	33.2 ± 0.9^{a}	15.1 ± 6.1^{ab}	25.6 ± 0.8^{c}
Leaf-stalks	Without I and F	2.1 ± 0.5^{b}	10.7 ± 0.6^{ab}	5.2 ± 1.6^{a}	11.2 ± 0.4^{a}	5.1 ± 2.0^{b}	11.1 ± 0.3^{a}	4.6 ± 2.3^{a}	8.8 ± 0.4^{b}
	Without I, with F	2.5 ± 0.5^{b}	7.9 ± 0.6^{c}	8.3 ± 1.6^{a}	10.6 ± 0.4^{a}	13.7 ± 2.0^{a}	10.5 ± 0.3^{a}	-2.1 ± 2.3^{a}	7.8 ± 0.4^{b}
	With I, without F	2.5 ± 0.5^{b}	9.8 ± 0.6^{b}	6.0 ± 1.6^{a}	10.9 ± 0.4^{a}	9.4 ± 2.0^{ab}	10.3 ± 0.3^{a}	6.3 ± 2.3^{a}	10.1 ± 0.4^{a}
	With I and F	4.2 ± 0.5^{a}	11.7 ± 0.6^{a}	8.2 ± 1.6^{a}	9.8 ± 0.4^{a}	8.9 ± 2.0^{ab}	9.0 ± 0.3^{b}	5.5 ± 2.3^{a}	8.2 ± 0.4^{b}
Pseudo-stem	Without I and F	8.1 ± 2.1^{a}	38.4 ± 1.4^{a}	17.5 ± 5.2^{c}	41.3 ± 1.2^{a}	21.4 ± 7.2^{b}	38.2 ± 1.2^{bc}	38.6 ± 7.1^{a}	46.3 ± 1.4^{b}
	Without I, with F	13.1 ± 2.1^{a}	37.6 ± 1.4^{a}	36.4 ± 5.2^{ab}	43.6 ± 1.2^{a}	50.5 ± 7.2^{a}	41.0 ± 1.2^{ab}	17.4 ± 7.1^{a}	44.6 ± 1.4^{b}
	With I, without F	9.8 ± 2.1^{a}	37.8 ± 1.4^{a}	21.9 ± 5.2^{bc}	44.4 ± 1.2^{a}	34.8 ± 7.2^{ab}	36.8 ± 1.2^{c}	36.6 ± 7.1^{a}	45.5 ± 1.4^{b}
	With I and F	13.1 ± 2.1^{a}	33.8 ± 1.4^{a}	37.8 ± 5.2^{a}	45.3 ± 1.2^{a}	52.4 ± 7.2^{a}	44.2 ± 1.2^{a}	48.8 ± 7.1^{a}	53.4 ± 1.4^{a}
Corm	Without I and F	1.9 ± 0.6^{a}	10.5 ± 0.7^{a}	3.4 ± 1.0^{a}	9.0 ± 0.5^{ab}	5.1 ± 1.2^{a}	9.5 ± 0.7^{b}	7.5 ± 1.2^{a}	9.2 ± 0.6^{a}
	Without I, with F	3.2 ± 0.6^{a}	9.9 ± 0.7^{a}	5.5 ± 1.0^{a}	7.9 ± 0.5^{b}	7.1 ± 1.2^{a}	7.8 ± 0.7^{b}	5.1 ± 1.2^{a}	8.8 ± 0.6^{a}
	With I, without F	2.1 ± 0.6^{a}	8.1 ± 0.7^{a}	4.9 ± 1.0^{a}	10.2 ± 0.5^{a}	8.4 ± 1.2^{a}	11.9 ± 0.7^{a}	5.4 ± 1.2^{a}	8.4 ± 0.6^{a}
	With I and F	3.7 ± 0.6^{a}	9.9 ± 0.7^{a}	5.1 ± 1.0^{a}	7.5 ± 0.5^{b}	5.8 ± 1.2^{a}	7.8 ± 0.7^{b}	8.3 ± 1.2^{a}	6.5 ± 0.6^{b}
Roots	Without I and F	1.8 ± 0.6^{a}	9.6 ± 0.6^{a}	2.6 ± 0.8^{a}	7.5 ± 0.7^{a}	2.9 ± 0.9^{a}	7.4 ± 0.4^{a}	6.1 ± 1.1^{a}	8.6 ± 0.5^{a}
	Without I, with F	3.0 ± 0.6^{a}	9.4 ± 0.6^{a}	4.2 ± 0.8^{a}	7.5 ± 0.7^{a}	4.4 ± 0.9^{a}	5.1 ± 0.4^{b}	4.6 ± 1.1^{a}	7.7 ± 0.5^{ab}
	With I, without F	2.6 ± 0.6^{a}	10.9 ± 0.6^{a}	2.4 ± 0.8^{a}	7.9 ± 0.7^{a}	3.6 ± 0.9^{a}	6.2 ± 0.4^{ab}	6.7 ± 1.1^{a}	7.7 ± 0.5^{ab}
	With I and F	4.0 ± 0.6^{a}	10.3 ± 0.6^{a}	4.2 ± 0.8^{a}	7.1 ± 0.7^{a}	3.9 ± 0.9^{a}	5.8 ± 0.4^{b}	7.3 ± 1.1^{a}	6.4 ± 0.5^{b}

***Note*:** least square means in each cell within the column of a specific stage of plant growth with different letter superscripts (a-c) are significantly different at $p<0.05$, n=16

4.3.5 K absorption and distribution among plant organs

The positive effect of shade on dry matter production generally enhanced K absorption among abaca organs. Statistical analysis revealed that the effect of shade varied significantly relative to the developmental stage of the crop; that is, at seedling ($p\leq0.01$), early vegetative ($p\leq0.05$) and flagleaf stage ($p\leq0.05$). There was no significant effect (except for corm) documented during the late vegetative stage.

It was observed that the normal pattern of K distribution among abaca organs was in the order pseudostem>leaves>roots>leafstalks>corm. This pattern was relatively similar to P distribution where higher share was allocated to the pseudostem and leaves. However, both patterns primarily vary on the leafstalks, corm and roots. Table 4.9 shows that high amount of K was partitioned on the roots than leafstalks and corm. Meanwhile, high quantity of P was distributed on the leafstalks than corm and roots.

Table 4.10 shows that irrigation-fertilization considerably enhanced K absorption at seedling ($p\leq0.01$), early vegetative ($p\leq0.05$) and late vegetative ($p\leq0.05$) stage but there was no significant effect at flagleaf stage. Analysis of variance confirmed that fertilizer application influenced the amount of K partitioned to the different abaca organs. A higher amount of K was recorded in abaca fertilized with NPK than in those plants without any NPK fertilization. On the other hand, supplemental irrigation did not influence the uptake of K.

Table 4.9 K absorption (g plant^{-1}) and proportional distribution (%) among abaca organs at different developmental stages as affected by shade across irrigation-fertilization treatments

Plant Organs	Shade Treatments	Stages of Plant Growth							
		Seedling		Early vegetative		Late vegetative		Flagleaf	
		Absorption	Distribution	Absorption	Distribution	Absorption	Distribution	Absorption	Distribution
Leaves	0% shade	44.0±21.4^{b}	26.9±1.2^{a}	88.0±34.8^{a}	23.0±0.8^{a}	373.2±80.6^{a}	20.4±0.6^{a}	-21.7±56.7^{b}	14.6±0.6^{c}
	30% shade	114.2±21.4^{a}	25.5±1.2^{a}	142.8±34.8^{a}	23.7±0.8^{a}	310.8±80.6^{a}	22.5±0.6^{a}	-100.1±56.7^{b}	16.4±0.6^{b}
	40% shade	133.4±21.4^{a}	26.1±1.2^{a}	183.5±34.8^{a}	24.3±0.8^{a}	238.1±80.6^{a}	20.7±0.6^{a}	239.9±56.7^{a}	18.2±0.6^{b}
	50% shade	142.9±21.4^{a}	24.2±1.2^{a}	97.4±34.8^{a}	24.3±0.8^{a}	486.2±80.6^{a}	20.3±0.6^{a}	285.1±56.7^{a}	22.6±0.6^{a}
Leaf-stalks	0% shade	12.9±8.0^{c}	9.0±0.6^{bc}	52.7±21.8^{b}	9.3±0.5^{b}	235.9±50.7^{a}	11.7±0.4^{a}	-0.5±30.9^{b}	7.2±0.4^{b}
	30% shade	37.9±8.0^{ab}	8.5±0.6^{c}	104.8±21.8^{ab}	10.4±0.5^{b}	202.1±50.7^{a}	13.2±0.4^{a}	-4.4±30.9^{b}	7.7±0.4^{b}
	40% shade	51.5±8.0^{bc}	10.4±0.6^{ab}	123.3±21.8^{a}	13.7±0.5^{a}	168.1±50.7^{a}	12.9±0.4^{a}	76.2±30.9^{ab}	8.2±0.4^{b}
	50% shade	67.1±8.0^{a}	12.0±0.6^{a}	41.2±21.8^{b}	10.3±0.5^{b}	344.5±50.7^{a}	12.5±0.4^{a}	109.0±30.9^{a}	9.6±0.4^{a}
Pseudo-stem	0% shade	49.6±27.0^{b}	29.1±1.3^{c}	221.7±55.1^{a}	37.8±1.2^{b}	824.1±161.0^{a}	43.8±1.3^{b}	603.0±128.9^{a}	57.0±1.4^{a}
	30% shade	157.7±27.0^{a}	34.2±1.3^{b}	229.1±55.1^{a}	38.0±1.2^{b}	796.7±161.0^{a}	42.8±1.3^{b}	533.3±128.9^{a}	55.2±1.4^{ab}
	40% shade	188.7±27.0^{a}	38.8±1.3^{a}	290.0±55.1^{a}	36.6±1.2^{b}	771.6±161.0^{a}	45.6±1.3^{ab}	727.8±128.9^{a}	52.2±1.4^{bc}
	50% shade	201.5±27.0^{a}	35.2±1.3^{ab}	205.8±55.1^{a}	45.1±1.2^{a}	1189.2±161.0^{a}	48.1±1.3^{a}	536.8±128.9^{a}	50.7±1.4^{c}
Corm	0% shade	21.2±7.6^{b}	13.8±0.8^{a}	40.8±14.7^{ab}	14.3±0.7^{a}	161.7±24.7^{a}	10.8±0.7^{a}	66.1±11.4^{ab}	6.5±0.4^{a}
	30% shade	57.1±7.6^{a}	12.8±0.8^{a}	76.4±14.7^{a}	15.5±0.7^{a}	99.1±24.7^{ab}	9.8±0.7^{a}	36.8±11.4^{b}	5.3±0.4^{ab}
	40% shade	38.7±7.6^{ab}	7.4±0.8^{b}	81.0±14.7^{a}	11.0±0.7^{b}	72.4±24.7^{b}	7.1±0.7^{b}	89.0±11.4^{a}	5.0±0.4^{b}
	50% shade	42.8±7.6^{a}	7.8±0.8^{b}	31.2±14.7^{b}	7.4±0.7^{c}	155.5±24.7^{a}	7.6±0.7^{b}	33.6±11.4^{b}	2.5±0.4^{c}
Roots	0% shade	33.6±15.8^{b}	21.1±1.0^{a}	26.5±13.4^{b}	15.6±1.1^{a}	200.7±36.8^{a}	13.4±0.8^{a}	157.6±33.7^{a}	14.8±0.8^{a}
	30% shade	75.9±15.8^{a}	19.0±1.0^{ab}	48.7±13.4^{ab}	12.5±1.1^{a}	135.8±36.8^{a}	11.9±0.8^{a}	125.6±33.7^{a}	15.4±0.8^{a}
	40% shade	86.7±15.8^{a}	17.3±1.0^{b}	82.8±13.4^{a}	14.4±1.1^{a}	128.7±36.8^{a}	13.7±0.8^{a}	239.0±33.7^{a}	16.4±0.8^{a}
	50% shade	120.6±15.8^{a}	20.8±1.0^{a}	48.2±13.4^{ab}	12.8±1.1^{a}	160.1±36.8^{a}	11.5±0.8^{a}	226.9±33.7^{a}	14.6±0.8^{a}

***Note*:** least square means in each cell within the column of a specific stage of plant growth with different letter superscripts (a-c) are significantly different at $p<0.05$, n=16

Table 4.10 K absorption (g plant^{-1}) and proportional distribution (%) among abaca organs at different developmental stages as affected by irrigation-fertilization across shade treatments

Plant Organs	Shade Treatments	Stages of Plant Growth							
		Seedling		Early vegetative		Late vegetative		Flagleaf	
		Absorption	Distribution	Absorption	Distribution	Absorption	Distribution	Absorption	Distribution
Leaves	Without I and F	65.0±21.4^{b}	25.5±1.2^{a}	93.4±34.8^{a}	25.7±0.8^{a}	186.5±80.6^{b}	20.2±0.6^{a}	142.3±56.7^{a}	19.5±0.6^{a}
	Without I, with F	113.1±21.4^{ab}	24.7±1.2^{a}	136.0±34.8^{a}	21.9±0.8^{b}	537.5±80.6^{a}	22.4±0.6^{a}	-32.6±56.7^{a}	17.6±0.6^{ab}
	With I, without F	91.1±21.4^{b}	26.5±1.2^{a}	114.0±34.8^{a}	23.2±0.8^{ab}	328.8±80.6^{ab}	20.6±0.6^{a}	173.1±56.7^{a}	17.9±0.6^{ab}
	With I and F	165.3±21.4^{a}	26.1±1.2^{a}	168.3±34.8^{a}	24.5±0.8^{a}	355.6±80.6^{ab}	20.8±0.6^{a}	120.3±56.7^{a}	16.7±0.6^{b}
Leaf-stalks	Without I and F	30.3±8.0^{b}	11.3±0.6^{a}	28.2±21.8^{b}	10.4±0.5^{b}	122.8±50.7^{b}	12.2±0.4^{b}	50.8±30.9^{a}	7.3±0.4^{c}
	Without I, with F	42.0±8.0^{b}	9.3±0.6^{bc}	133.3±21.8^{a}	13.7±0.5^{a}	358.1±50.7^{a}	13.8±0.4^{a}	-23.3±30.9^{a}	7.4±0.4^{bc}
	With I, without F	31.6±8.0^{b}	8.6±0.6^{c}	29.8±21.8^{b}	9.0±0.5^{c}	223.6±50.7^{ab}	12.0±0.4^{b}	76.8±30.9^{a}	9.4±0.4^{a}
	With I and F	65.5±8.0^{a}	10.7±0.6^{ab}	130.7±21.8^{a}	10.7±0.5^{b}	246.0±50.7^{ab}	12.2±0.4^{b}	76.0±30.9^{a}	8.6±0.4^{ab}
Pseudo-stem	Without I and F	91.3±27.0^{b}	34.3±1.3^{a}	145.0±55.1^{b}	37.1±1.2^{b}	482.5±161.1^{b}	44.3±1.3^{a}	578.2±128.9^{a}	50.3±1.4^{c}
	Without I, with F	167.4±27.0^{ab}	35.1±1.3^{a}	299.0±55.1^{ab}	38.6±1.2^{b}	1151.6±161.1^{a}	44.2±1.3^{a}	412.7±128.9^{a}	55.3±1.4^{ab}
	With I, without F	115.4±27.0^{b}	33.2±1.3^{a}	166.0±55.1^{b}	38.5±1.2^{b}	852.4±161.1^{ab}	43.9±1.3^{a}	710.2±128.9^{a}	51.6±1.4^{bc}
	With I and F	223.4±27.0^{a}	34.8±1.3^{a}	336.7±55.1^{a}	43.2±1.2^{a}	1095.2±161.1^{a}	47.8±1.3^{a}	699.9±128.9^{a}	57.7±1.4^{a}
Corm	Without I and F	23.6±7.6^{b}	10.9±0.8^{a}	30.1±14.7^{a}	12.3±0.7^{a}	105.5±24.7^{a}	9.1±0.7^{a}	59.7±11.4^{a}	5.4±0.4^{ab}
	Without I, with F	49.9±7.6^{a}	10.9±0.8^{a}	73.5±14.7^{a}	12.7±0.7^{a}	150.5±24.7^{a}	8.6±0.7^{a}	50.0±11.4^{a}	4.6±0.4^{b}
	With I, without F	33.3±7.6^{ab}	10.2±0.8^{a}	68.7±14.7^{a}	13.3±0.7^{a}	115.5±24.7^{a}	10.2±0.7^{a}	64.8±11.4^{a}	6.2±0.4^{a}
	With I and F	53.1±7.6^{a}	9.8±0.8^{a}	57.1±14.7^{a}	10.0±0.7^{b}	117.1±24.7^{a}	7.4±0.7^{a}	51.0±11.4^{a}	3.1±0.4^{c}
Roots	Without I and F	42.8±15.8^{b}	18.0±1.0^{a}	37.8±13.4^{a}	14.5±1.1^{a}	113.9±36.8^{a}	14.2±0.8^{a}	177.5±33.7^{a}	17.5±0.8^{a}
	Without I, with F	91.8±15.8^{a}	20.0±1.0^{a}	62.4±13.4^{a}	13.1±1.1^{a}	193.3±36.8^{a}	11.1±0.8^{b}	155.6±33.7^{a}	15.0±0.8^{b}
	With I, without F	69.6±15.8^{ab}	21.4±1.0^{a}	47.2±13.4^{a}	16.0±1.1^{a}	155.2±36.8^{a}	13.4±0.8^{ab}	209.6±33.7^{a}	14.9±0.8^{b}
	With I and F	112.7±15.8^{a}	18.7±1.0^{a}	58.8±13.4^{a}	11.7±1.1^{a}	162.8±36.8^{a}	11.8±0.8^{b}	206.4±33.7^{a}	13.8±0.8^{b}

***Note*:** Least square means in each cell within the column of a specific stage of plant growth with different letter superscripts (a-c) are significantly different at $p<0.05$, n=16

4.4 Discussion

Total dry matter accumulation differed significantly among sample plants in response to shade and irrigation-fertilization treatments at different development stages of abaca. Results showed that shade significantly enhanced leaf and pseudostem mass ratio at early vegetative and flagleaf stage. This enhancement effect of shade at early vegetative stage was due to the fact that high radiation (temperature) caused photoinhibition and/or photooxidative damage (leaf sunburn) of abaca plants grown under full sunlight (0% shade). The burning led to the reduction in the number of leaves per plant which reduced net assimilation rate (Kamaluddin and Grace, 1991; Osmond, 1994; Goltsev et al., 2003) and ultimately the total amount of dry matter produced and allocated on both leaves and pseudostem. Lambers at al. (1998) reported that temperature has a major effect on enzymatically catalyzed reactions and membrane processes; therefore, it affects photosynthesis and net assimilation. Furthermore, the low N absoption at seedling and early vegetative stage (Table 4.5) substantiated the detrimental effect of photoinhibition on photosynthetic capacity of abaca grown under full sunlight (0% shade). Lambers et al. (1998) revealed that an inadequate supply of nitrogen leads to a decrease in the biochemical determinants of photosynthetic capacity and stomatal conductance. On the other hand, the differential leaf senescence among abaca plants grown in different shade treatments influenced biomass distribution at flagleaf stage. Results showed that shade had significantly prolonged leaf longevity (Lambers et al., 1998; Valladares and Niinemets, 2008; Saifuddin et al., 2010) of abaca grown under 40% and 50% shade which resulted to high leaf and pseudostem mass ratio at harvest (flagleaf stage). In contrast, the timely leaf senescence observed on abaca under 0% and 30% shade reduced the amount of biomass allocation to the leaves but considerably enhanced the distribution to the pseudostem (Table 4.3).

The high dry matter production among abaca treated with NPK fertilizer and/or combination of irrigation-fertilization across shade treatments was mainly due to higher stalk yield. According to Lambers et al. (1998), plants from nutrient-rich sites tend to produce more biomass per unit nutrient in the plant. These findings are in agreement with the results of Bales et al. (1981), Alemania et al. (1982), Alcober (1986), Armecin et al. (2005), Armecin and Gabon (2008) indicating that pseudostem dry matter of abaca increased with the increase in plant height due to fertilizer application. The increase in biomass production had significantly influenced the distribution of dry matter among abaca organs. This was more pronounced at vegetative stages (early and late) where rapid plant growth was recorded (Table 4.4). This is consistent with the study of Hossain et al. (2010a, 2011b) on kenaf (*Hibiscus cannabinus*) for fiber production. On the other hand, Lambers et al. (1998) found that plants have some capacity to acclimate to a range in soil conditions. One of these acclimations is morphological where plants usually increase their root mass ratio when nitrogen is limited for crop growth. This confirmed the data in Table 4.4 where lower root mass ratio was recorded on abaca fertilized with NPK than those plants without NPK fertilization. The effect was significant and evident at late vegetative ($p=0.0110$) and flagleaf ($p=0.0054$) stages of crop growth.

On the other hand, fertilizer application or combination of irrigation-fertilization triggers the crop to allocate higher share of dry matter to the pseudostem than leaves at early vegetative stage. This prompted the plant to shift earlier the dry matter distribution from the usual pattern at early vegetative stage. Based on the results, the usual dry matter distribution among abaca organs independent of the effects of shade and irrigation-fertilization was in the order leaves>pseudostem>corm>roots (seedling and early vegetative stage) and pseudostem>leaves>corm>roots (late vegetative and flagleaf stage) of crop growth.

Plants absorb and allocate nutrients into various organs in a balanced system. For abaca, the proportion of nutrients among plant organs differed significantly due to environmental (Halos, 2008) and soil (Lambers et al., 1998) conditions as well as the inherent differences between abaca varieties (Armecin, 2008). The findings of this study showed that N was abundant in the leaves. Plants require

2-5% of plant dry weight nitrogen (Marschner, 1995) and roughly half of the total N in a leafy plant is found in the chloroplasts (Epstein, 1972). Meanwhile, Seginer (2004) reported that N concentration in the leaves of most field crops decreases as the plants grow. Lambers et al. (1998) pointed out that nutrients associated with metabolism (e.g., NPK) have highest concentrations when a leaf or other organ is first produced, then decline, first as the concentration becomes diluted by increasing quantities of cell-wall material during leaf expansion. Furthermore, K was found high in the pseudostem while P was evenly distributed in the leaves and pseudostem. This is consistent with the findings of Armecin (2008) indicating the same trend of NPK absorption among abaca organs.

Growth is an important component of nutrient uptake in plants (Turner and Lahav, 1986). In this study, the amount of nutrients (i.e., NPK) absorbed was influenced by the amount of growth made by each of the plant organs examined. However, the link between growth and nutrient uptake differed from one element to another in response to shade and irrigation-fertilization combinations as the crop developmental stage progresses. At vegetative phase (from seedling to late vegetative stage), the quantity of NPK absorbed and distributed among the organs was influenced by the changing pattern of dry matter distribution brought by differences in temperature due to radiation. Furthermore, changes in the normal pattern of NPK distribution among organs as affected by shade was visible at late vegetative stage particularly on abaca planted in 0% shade. This finding was in agreement with the study of Turner and Lahav (1986) on *Musa* (AAA group, Cavendish sub-group) grown in sunlit controlled-environment chamber which showed that the pattern of nutrients distribution among banana parts was influenced by the preferential allocation to particular organs as well as by the changing patterns of dry matter distribution brought by temperature. They further explained that the effect of temperature on the distribution of nutrients within the plant was influenced by the tendency of some nutrients to accumulate in particular organs and by the effect of temperature on the distribution of dry matter between organs. Lambers et al. (1998) pointed that environment strongly affects plant nutrient concentration by changing both allocation among organs and the composition of individual tissues. This is true for nutrients associated with metabolism and more mobile elements (i.e., NPK) where temperature significantly influenced the concentration of these nutrients in leaves, pseudostem, corms and roots (Lahav and Turner, 1985). Meanwhile, the application of fertilizer and combination of irrigation-fertilization considerably enhanced NPK absorption.

At generative phase (flagleaf stage), shade significantly influenced N absorption and distribution among abaca organs. This could be attributed to the differential leaf senescence among abaca grown in the different shade treatments which could have probably influenced resorption or retranslocation of NPK. It is estimated that approximately half of the N and P content in the leaves is resorbed (Aerts, 1996; Killingbeck, 1996) or retranslocated (Kadir et al., 1998) to subsequent generations of suckers (Turner and Lahav, 1986) during senescence. This finding strongly substantiated the negative values of NPK absorption on the leaves and leafstalks of abaca grown in 0% and 30% shade. Furthermore, Chapin and Kedrowski (1983) reported that resorption is positively correlated with leaf mass loss during senescence. This corroborates the result of this study as presented in Table 4.3 where shade negatively affected leaf mass ratio on abaca grown in 0% and 30% shade at flagleaf stage.

4.5 Conclusions

The study was conducted to investigate the effect of shade on biomass production and allocation as well as NPK absorption and distribution among abaca organs. The study also aimed to examine if irrigation and fertilization could offset the effect of shade on biomass production and nutrient absorption in all abaca plant parts. Based on the results of the study it is concluded that shade effectively prevent the detrimental effect of photoinhibition on the photosynthetic capacity of abaca (if planted in full sunlight) which considerably improved biomass production and dry matter allocation among abaca organs. The amount of NPK absorbed by each organ was influenced by temperature causing photooxidative damage at seedling stage and differential leaf senescence at flagleaf stage. This significantly affected the pattern of biomass allocation and NPK distribution among abaca plant parts.

It is further concluded that the application of fertilizer considerably enhanced biomass production but did not change the usual pattern of biomass and NPK distribution. To promote high NPK absorption among abaca plant parts, it is highly recommended that fertilizer application should be coupled with irrigation. However, results showed that irrigation and fertilizer application cannot offset or equalize the positive effect of shade on biomass production and NPK absorption among plant organs.

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4.8 Supporting Information

Photo S1 Abaca planted in open treatment with burned leaves one month after planting.

Photo S2 Abaca plants grown in open treatment with extremely injured leaves (photooxidative damage) due to high radiation three months after planting.

5. General Discussion

Leyte Island's economy basically revolves around agriculture where the main source of income for the majority of population comes from the production of crops, livestock and marine products. Coconut, abaca and root crops planted in *kaingin* (slash-and-burn) had been significant components of cultivated forestlands in the island (Acosta, 1991; Dargantes, 1996). It is estimated that forest cover was only 12.1% of the forestland in 1990 (Dargantes, 1996) where the main cause of this decline can be attributed to extensive conversion of forest land into coconut and abaca plantations (Groetschel et al., 2001). Hence, the addition of new industry like Daimler AG that was successful in using abaca for the exterior parts of Mercedes-Benz A class passenger (DaimlerChrysler, 2004; Oliver, 2004) and the use of abaca fiber as replacement for asbestos in the United Kingdom has created a big boost in its demand (Armecin and Gabon, 2008). This situation may lead to further encroachment of abaca plantation to forestland and cutting down of forest trees. Hence, a paradigm shift on abaca-based agroecological production systems is necessary where the crop could be used as a tool to encourage upland farmers to plant rather than to cut down trees in cultivating abaca.

Until now, there is still disagreement on the need for shade trees in abaca cultivation (Halos, 2008). Sievert (2009) reported that shade trees act more as windbreaks in typhoon-prone areas such as Southern Luzon or Leyte. Anecdotal reports revealed that abaca planted in open areas or full sunlight in Davao, Southern Philippines (where strong winds rarely strike) yielded more and stronger fiber than that grown in shade (Halos, 2008; Sievert, 2009). However, there are only two scientific and published reports available involving studies of abaca growth under different shade levels and they have conflicting results. The pioneering study of Copeland (1911) where he found that growth rate and dry weight of abaca plants grown under shade were lower than those of abaca grown without shade. The second study was of Batugal et al. (1977) where they documented improved growth and yield under partial shading at 33% and 66% than in open space. These two studies were conducted 101 and 35 years ago, respectively, and no follow-up study was conducted to confirm any of the two conflicting results being reported and published. Hence, this study was conducted to ascertain the ecophysiological and agronomic response of abaca grown in different shade conditions, water and nutrient management systems in Leyte. Likewise, fiber strength and tenacity was measured to determine if shade and irrigation-fertilization will affect fiber quality for industrial use.

The result of this study showed that the vegetative growth of abaca planted in 0% shade was negatively affected by high radiation (temperature) causing photoinhibition and photooxidative damage (Photo S1 and S2 Chapter 4) of the crop at seedling and early vegetative stages. This significantly affected NPK plant uptake (Tables 4.5, 4.7 and 4.9). Turner and Lahav (1985) reported that growth is an important component of nutrient uptake in all plants. Hence, if growth is reduced (by environmental or soil conditions) then the amount of nutrient absorbed will also be reduced. On the other hand, the application of fertilizer and/or combination of irrigation-fertilization across shade treatments consistently and considerably improved vegetative growth (i.e., plant height, pseudostem length and base girth), dry matter production and NPK absorption. Lambers et al. (1998) reported that plants from nutrient-rich sites tend to produce more biomass per unit nutrient in the plant. However, irrigation and fertilizer application were not able to prevent or avoid the negative effect of photoinhibition and photooxidative damage of abaca grown in full sunlight. These findings clearly confirm that abaca needs shade to protect them from high temperature that may cause detrimental effect on both morphological and physiological performance of the crop at seedling and early vegetative stages.

The most prominent effect of shade on the morphological growth parameters of abaca was on the significant improvement on plant height, cumulative leaf area, pseudostem length and base girth at seedling (Photo 5.1) and early vegetative stages of crop growth (Table 2.2). Likewise, biomass production (Table 4.2) and nutrient absorption significantly increased with reducing irradiance.

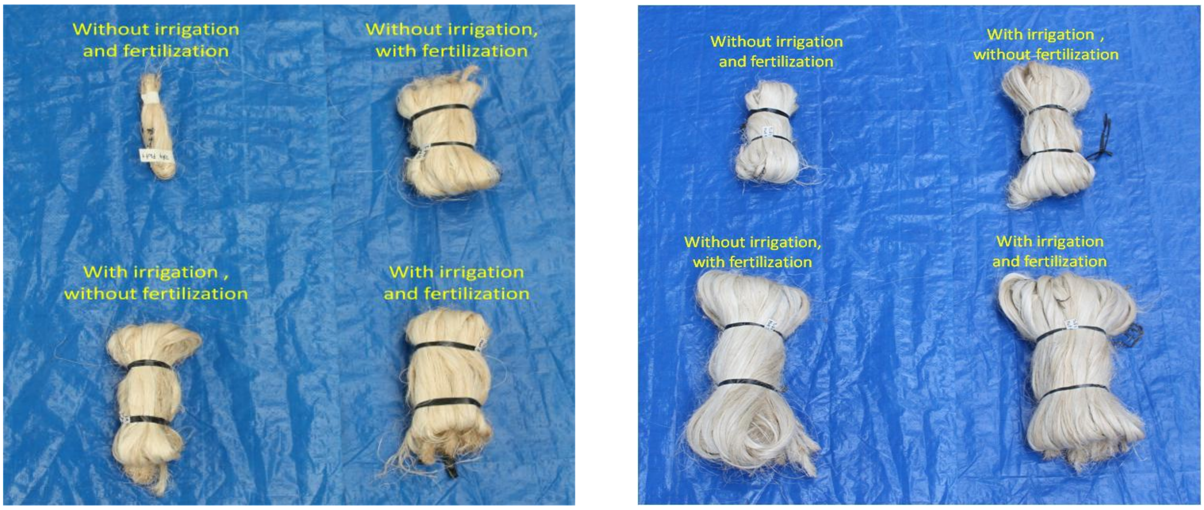
The application of NPK fertilizer and combination of irrigation-fertilization consistently and positively improved all the growth parameters starting from seedling stage until flagleaf stage. However, it was observed that abaca plants developed some capacity to acclimate to a range in nutrient conditions at a certain stage of crop development. This acclimation was morphological where the plants usually increase their root mass ratio when nutrients were limited for crop growth (Lambers et al., 1998). Brouwer (1962) found that root mass ratio is usually enhanced by growth at a low nutrient supply. In this study, lower root mass ratio was recorded on abaca treated with NPK fertilizer than those without fertilization.

0% shade 30% shade 40% shade 50% shade

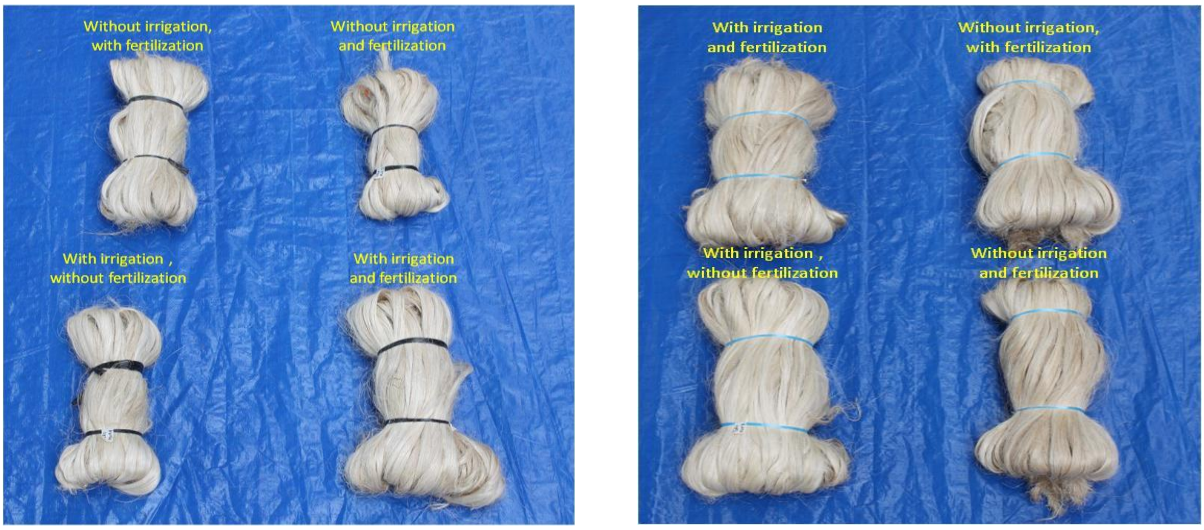
Photo 5.1 Abaca plants grown in different shade treatments without irrigation and fertilizer application at seedling stage (3 months after planting)

On the other hand, the notable physiological response to shade was on the significant effect on net assimilation rate at seedling stage. It was observed that net assimilation rate (Table 2.3) considerably increased on abaca grown in shaded compared to those planted in full sunlight. Lambers et al. (1998) pointed out that temperature has a major effect on enzymatically catalyzed reactions and membrane processes. Hence, it affects photosynthesis and net assimilation. Therefore, this positive effect was primarily because shade has fully protected the abaca from high radiation (temperature) that successfully prevented photoinhibition and/or photooxidative damage on its leaves. Lambers et al. (1998) reported that species that are genetically well-adapted to shade often have a very restricted capacity to acclimate to a high level of irradiance that can cause photodamage. This is when the energy absorbed by the photosystems exceeds the energy that can be used in photochemistry. In this case, abaca as shade plant lacks a regulation mechanism that avoids photodamage, where the excess energy absorbed by the light-harvesting complex is dissipated as heat. This regulation mechanism ensures that no competing dissipation of energy occurs when light is limiting for photosynthesis, whereas damage is prevented when light is absorbed in excess (Demmig et al., 1987; Johnson et al., 1993a; 1993b). Furthermore, the low N absorption at seedling and early vegetative stages of abaca grown in 0% shade substantiated the detrimental effect of photoinhibition on photosynthetic capacity. Lambers et al. (1998) found that an inadequate supply of nitrogen leads to a decrease in the biochemical determinants of photosynthetic capacity and stomatal conductance.

With regards to agronomic response, shade considerably increased fiber yield to as much as 165%. This was mainly due to the positive effect of shade on stalk or pseudostem yield. The abaca plants harvested in 50% shade produced longer, bigger, and heavier pseudostem than those harvested in 0% shade. Furthermore, fiber yield in 30% and 40% shade treatments was statistically similar but significantly lower than 50% shade and higher than those in 0% shade treatment (Photo 5.2).



0% shade 30% shade



40% shade 50% shade

Photo 5.2 Fiber yield in different shade and irrigation-fertilization treatments

The combination of irrigation and fertilizer application further enhanced fiber yield to as much as 41%. This was because the application of NPK fertilizer consistently and positively affected the pseudostems' length, girth and weight of the plant. The results of statistical analysis confirmed the effect of NPK fertilizer application on fiber yield where a significant difference was observed at probability≤0.01 on abaca planted in plots with NPK fertilizer. Alcober (1986) reported that fiber yield depends on the number of harvestable stalks and the physical characteristics of the stalks at harvest (Photo 5.3). He found that there was a significant correlation between stalk weight, length and fiber yield. This was consistent with the result in this study where there were highly significant correlations between fiber yield and pseudostem or stalk weight (r=0.93) and length (r=0.87). Meanwhile, there was no significant effect observed on plants grown in plots with supplemental irrigation compared to the control treatment which probably suggests that the incidental rainfall during the period of the experiment was sufficient for plant growth and development. The result could be different during long drought periods due to El Niño or climate change.

0% shade 30% shade 40% shade 50% shade

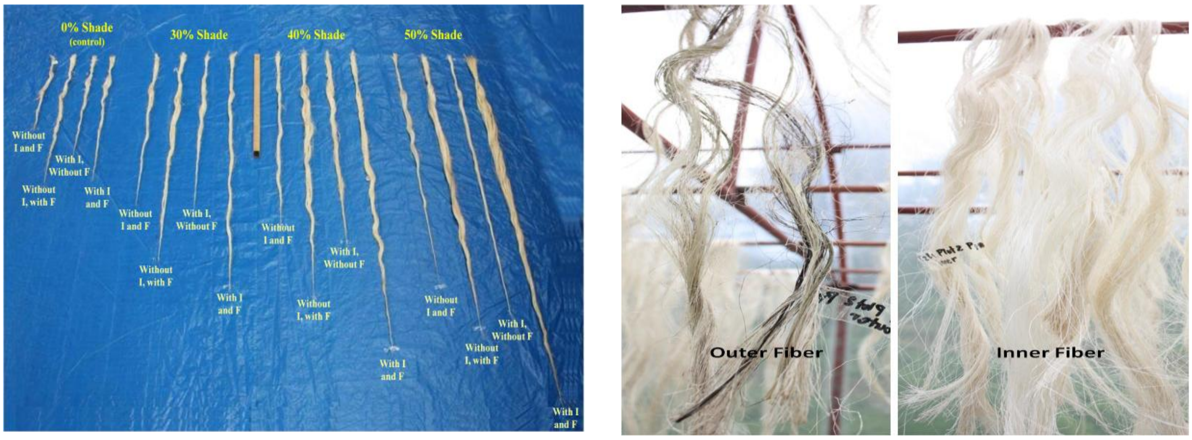
Photo 5.3 Numbers of harvested stalks and pseudostems' length of abaca grown at different shade treatments without irrigation and fertilizer application

The data on fiber recovery (Chapter 3Table 1) revealed that outer leaf sheaths had lower fiber recovery than the inner leaf sheaths. The low fiber recovery from the outer leaf sheaths was probably due to the developed parenchyma cells attached to the fibers and presence of stigmata which made the surface of fiber rough, causing more friction during stripping. Moreover, it was documented during tuxy (Photo 5.4A) and stripping activities that the outer leaf sheaths were always shorter than those in the inner leaf sheaths which offered difficulty in winding tuxies around the spindle that caused lower fiber recovery (Photo 5.4B).

A B

Photo 5.4 Tuxies from outer and inner leaf sheaths (A) and winding of tuxies (from the outer leaf sheaths) around the spindle of the stripping machine (B)

The fiber quality (i.e., tensile strength, fineness, color) was not negatively affected by any of the experimental treatments applied except for fiber length which was strongly correlated (r=0.98) to leaf sheath's length (Photo 5.5A). Fibers from the outer leaf sheaths were stronger than those from inner leaf sheaths. This may be due to the physiological age which varies among the leaf sheaths in the pseudostem or stalk. Inner leaf sheaths are always physiologically younger than the outer regardless of the age of the plant. Likewise, it was observed that the outer fiber had darker color compared to inner fiber (Photo 5.5B). The dark color of the outer fiber was due to high concentration of pigments since these are usually exposed to sunlight.



A B

Photo 5.5 Average fiber length of the sample plants in relation to pseudostem's length as influenced by shade and irrigation-fertilization (A). Color of outer and inner fiber after stripping and during air drying (B)

The effect of photoinhibition and oxidative damage (Kalamuddin and Grace, 1991; Demmig et al., 1987; Lambers et al., 1998) on abaca (if grown in full sunlight) has stimulated the plant to acclimate both morphologically and physiologically, which has been found in most shade tolerant species (Valladares and Niinemets, 2008). Based on the results of this study, the influence of shade on the vegetative growth performance of abaca has some widespread implications on the agronomic response (i.e., fiber yield and fiber recovery) of the crop under conditions of high temperature and solar radiation which is common in tropical countries like the Philippines. Hence, the result of this study may provide additional scientific information on how to mitigate the impact of increasing temperature on abaca fiber production due to climate change.

In addition, the significant increase of abaca fiber yield (165%) by merely reducing irradiance using shade trees could be an important factor in promoting the benefits of the plant as an intermediate crop in existing slash-and-burn and coconut monoculture farmlands. This will limit or minimize the expansion of abaca plantations in the remaining forestland considering the increasing demand of abaca fiber. Likewise, the improvement of existing abaca-based monoculture farms by means of encouraging farmers to plant indigenous shade trees in between abaca hills could be a major shift of abaca cultivation in the Philippines. In this case, abaca could be used as a tool that will encourage farmers to plant trees that have a positive implication in addressing climate change issues under the land use and forestry activities to offset CO_2 emission as stipulated under Article 3.4 of the Kyoto Protocol.

Finally, abaca-based cultivation is more or less a closed nutrient production system where only 1.5 to 2% of the pseudostems' total biomass is taken out in the form of fiber. In this study a maximum of 1.2±0.02% in 50% shade and 1.09±0.02% in irrigation-fertilization treatments was extracted as dried fiber. Abaca is a long-term perennial crop and the plantation may even remain productive and profitable for up to twenty years of cultivation (Sievert, 2009). However, longevity is usually influenced by many factors and one of these is nutrient management. In this study, NPK were concentrated and distributed in the leaves and pseudostem of abaca. However, the fibers are only extracted from the pseudostem and usually farmers tend to assemble the harvested stalks or pseudostems in one spot within their farm during tuxying and stripping activities. Hence, it is highly recommended that waste materials should be uniformly distributed back to the farmland to conserve the nutrient which could be used and recycled by the subsequent next generations of suckers.

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Summary

Abaca (*Musa textilis* Née) is closely related to edible bananas (*Musa acuminata* Colla and *M. balbisiana* Colla). Abaca is indigenous to the understorey of the Philippines' tropical lowland evergreen rainforests and grown primarily for its fibres. The plant requires specific climatic and soil conditions; hence, its cultivation is limited to defined regions. Abaca grows best on a fertile soil of recent volcanic or alluvial origin with good moisture retention, rainfall of 2000-3000 mm year^{-1}, no dry season, humidity range of 78-88 %, optimum temperature range of 20-27 °C and at altitudes up to 1000 meters. The Filipinos were the first to domesticate, cultivate, process, trade and even use abaca products as an instrument in paying taxes. The abaca industry continues to be one of the country's major pillars in terms of employment generation and foreign exchange earnings. The industry provides livelihood to more than 1.5 million Filipinos who, directly or indirectly, depend on it for a living. From 2001 to 2010, the abaca industry generated USD82.1 million year^{-1} from the exports of raw fiber and manufactures.

Abaca is currently cultivated in almost all provinces in the Philippines except the Ilocos region, Cagayan Valley, Region 3, Cavite and Batangas. Abaca plants can be propagated by seeds or by vegetative cloning (i.e., sucker, corm or seed pieces, eyebud or tissue culture). Abaca usually thrives in the shade beneath tall trees, especially important for protecting the young plants from the sun and the older, taller plants from wind breakage. However, there is still disagreement on the need for shade trees in abaca cultivation. Some scientists argued that shade trees only act more as windbreaks in typhoon-prone areas while others reported that abaca planted in open areas yielded more and stronger fiber than that grown in shade. Literature showed that there are only two scientific and published reports available involving studies of abaca growth under different shade levels and they have conflicting results. These two studies were conducted 101 years (Copeland, 1911) and 35 years (Batugal et al., 1977) ago and no follow-up study was conducted to confirm any of the two conflicting results being published. Hence, this study was conducted to ascertain the ecophysiological and agronomic response of abaca grown in different shade conditions, water and nutrient management systems in Leyte Island, Philippines.

The objectives of the study were to: (a) explore the influence of shade and irrigation-fertilization on the morphological and physiological performance of abaca; (b) investigate the effect of reducing light intensities by 30%, 40% and 50% of full sunlight on fiber yield and fiber quality; (c) determine the optimum light requirement of abaca plants to attain the optimum yield without affecting the quality of the fiber for industrial use; (d) examine the effect of shade and irrigation-fertilization on biomass production and allocation as well as on NPK absorption and distribution among abaca organs; and (e) find out if irrigation and fertilization could offset the effect of shade on biomass production, NPK absorption and fiber yield of abaca. Thus, field trials were established where light infiltration was reduced by 30%, 40%, and 50% of full sunlight using polypropylene shade nets. Irrigation was applied at a rate of 5 liters plant^{-1} application^{-1} day^{-1}. The frequency of irrigation was applied two times per day at seedling stage (1-3 months after planting), three times at the early vegetative stage (4-6 MAP), four times at the late vegetative stage (7-9 MAP), and five times at flagleaf stage (10-12 MAP). The reason for increasing the frequency of watering was due to an increase of emergence of new suckers. On the other hand, placement application of N, P_2O_5, K_2O using complete fertilizer was done at 14 g plant^{-1} in every three months for the first six months and was increased to 40 g plant^{-1} in every three months for the next six months after planting.

The results of this study showed that plant height, cumulative leaf area, pseudostem length and base girth of abaca significantly improved when the light was further reduced to 50%. The application of NPK fertilizer and combination of irrigation-fertilization further enhanced the growth performance of abaca. Statistical analysis showed that shade, NPK fertilization and combination of irrigation-

fertilization positively affected dry matter production, crop growth rate, leaf area ratio and net assimilation rate from seedling to flagleaf stage. Furthermore, biomass allocation and NPK distribution among abaca organs was significantly affected by high radiation and/or temperature at seedling and early vegetative stages, and differential leaf senescence at flagleaf stage where shade plays a considerable function. The amount of NPK absorbed by each organ was influenced by the growth made during the different stages of crop development. Meanwhile, irrigation and fertilizer application further improved biomass allocation that considerably increased NPK absorption and distribution among plant parts.

With regards to agronomic response, the abaca planted under different light regimes showed that 50% shade had significantly higher fiber yield compared to those that were under other light treatments since the plants pseudostem under such treatment were longer, bigger and heavier. The combination of irrigation and fertilization could further enhance fiber yield to as much as 141% (compared to the control) but this was not enough to offset the effects of shade on the physiological performance of the plant which significantly increased fiber yield to as much as 265% (compared to the control). Statistical analysis showed that shade and irrigation-fertilizer application had no significant effect on fiber fineness and tensile strength.

The superior productivity of abaca in response to shade was due to the avoidance of photoinhibition and photooxidative damage that negatively affected the abaca grown under full sunlight at seedling and early vegetative stage. Likewise, the detrimental effect of photoinhibition on the photosynthetic capacity of abaca grown in full sunlight significantly decreased biomass production and allocation among abaca organs. The amount of NPK absorbed by each organ was influenced by high radiation causing photooxidative damage at seedling stage and differential leaf senescence at flagleaf stage. This significantly affected the pattern of biomass allocation and NPK distribution among abaca plant organs. On the other hand, the application of fertilizer considerably enhanced biomass production but did not change the usual pattern of biomass and NPK distribution. To promote high NPK absorption among abaca plant parts, it is highly recommended that fertilizer application should be coupled with irrigation. However, results showed that irrigation and fertilizer application cannot offset or equalize the positive effect of shade on the vegetative growth, physiological performance, and NPK absorption among plant organs.

Furthermore, the optimum light to attain an optimum yield without jeopardizing fiber quality was 50% shade. However, if the crop is grown at this level of shade, proper horticultural management (i.e., fertilizer application and/or combination of irrigation-fertilization) has to be implemented to optimize its supply of nutrient as supported by the significant effects of fertilizer application on abaca growth in this study. This was further substantiated by the two-factor interaction effect of shade and irrigation-fertilization on outer leaf sheaths, inner leaf sheaths, and total fiber yield.

Zusammenfassung

Abaca (*Musa textilis* Née) ist nahe verwandt mit den Essbananen (*Musa acuminata* Colla und *M. balbisiana* Colla) und im Unterwuchs des tropischen, immergrünen Flachland-Regenwaldes auf den Philippinen heimisch. Die Pflanze wird hauptsächlich zur Faserproduktion angebaut und da ihr Anbau an bestimmte Klimabedingungen und Bodenverhältnisse gebunden ist, ist ihr Anbau regional beschränkt. Abaca gedeiht am besten auf fruchtbaren vulkanischen oder alluvialen Böden jüngeren Datums, bei einem Niederschlag von 2000-3000 mm Jahr^{-1} (keine Trockenzeit), bei einer Luftfeuchte von 78-88 %, bei einem optimalen Temperaturbereich von 20-27 °C und in Höhenlagen bis zu 1000 m. Die Philippiner waren die ersten, die Abaca domestizierten, kultivierten und verarbeiteten und die Abaca-Produkte dazu verwendeten Handel zu treiben oder sogar Steuern zu bezahlen. Die Abaca-Industrie zählt bis heute auf den Philippinen zu den wichtigsten Säulen wenn es um Arbeitplätze und ausländische Devisenerträge geht und stellt direkt oder indirekt die Existenzgrundlage für mehr als 1,5 Mio. Philippinen dar. Zwischen 2001 und 2010 erwirtschaftete die Abaca-Industrie durch den Export von Rohfasern und Industrieerzeugnissen 82,1 Mio USD Jahr^{-1}.

Abaca wird derzeit in fast allen Regionen der Philippinen angebaut mit Ausnahme der Ilocos Region, Cagayan Valley, Region 3, Cavite und Batangas. Die Pflanze kann durch Samen oder vegetativ vermehrt werden (z.B. Schösslinge, Stecklinge, Gewebekultur). Abaca gedeiht normalerweise im Schatten unter großen Bäumen, was vor allem den jungen Pflanzen Schutz vor Sonneneinstrahlung bietet und ältere, größere Pflanzen vor Windbruch schützt. Dennoch ist die Notwendigkeit schattenspendender Bäume für den Anbau von Abaca umstritten. Einige Forscher sind der Ansicht, dass schattenspendende Bäume lediglich als Windschutz in taifungefährdeten Gebieten notwendig sind und dass beim offenflächigen Anbau von Abaca im Gegensatz zum beschatteten Anbau mehr und kräftigere Fasern erwirtschaftet werden. In der Literatur gibt es jedoch lediglich zwei veröffentlichte, wissenschaftliche Studien zum Einfluss der Beschattungsintensität auf das Wachstum von Abaca, wobei beide Studien zu unterschiedlichen Ergebnissen kommen. Obwohl diese Studien bereits vor 101 Jahren (Copeland 1911) bzw. 35 Jahren (Batugal et al. 1997) veröffentlicht wurden, gibt es bis heute keine Folgestudien, die eines der widersprüchlichen Ergebnisse bestätigen würden. Aufgrund dessen wurde in der vorliegenden Arbeit primär der Einfluss der Beschattung auf ökophysiologische und argonomische Parameter von Abaca untersucht, aber auch der Einfluss des Nährstoff- und Wassermanagements. Die Versuche wurden als Freilandstudien auf der Insel Leyte, Philippinen, durchgeführt.

Die spezifischen Fragestellungen der Arbeit lauteten: (a) Einfluss der Beschattung, der Bewässerung und der Düngung auf morphologische und physiologische Eigenschaften von Abaca; (b) Einfluss der Lichtintensität (50, 60, 70 und 100 % volles Sonnenlicht) auf Faserertrag und -qualität; (c) Ermittlung der optimalen Lichtbedürfnisse von Abaca-Pflanzen für eine optimale Ertragsleistung bei gleichbleibender Faserqualität für industrielle Nutzung; (d) Einfluss der Beschattung, der Bewässerung und der Düngung auf die Biomasseproduktion und -verteilung sowie die NPK-Absorption und -Verteilung zwischen Pflanzenorganen; und (e) Inwieweit durch Bewässerung und Düngung der Einfluss der Beschattung auf die Biomasseproduktion, die NPK-Absorption und den Faserertrag von Abaca kompensiert werden kann. Zur Klärung dieser Fragestellungen wurden Feldversuche durchgeführt bei denen die Belichtung der Abaca-Bestände durch Sonnenlicht mit Beschattungsnetzen um 30, 40 und 50 % reduziert wurde. Die Bewässerungsintensität betrug 5 L Pflanze^{-1} Applikation^{-1} und es wurde im Keimlingsstadium [1-3 Monate nach Pflanzung (MNP)] zweimal pro Tag bewässert, im frühen vegetativen Stadium (4-6 MNP) dreimal pro Tag, im späten vegetativen Stadium (7-9 MNP) viermal pro Tag und im Fahnenblattstadium (10-12 MNP) fünfmal pro Tag. Die Bewässerungsfrequenz wurde mit zunehmendem Pflanzenalter erhöht, da zunehmend mehr Triebe ausgebildet wurden. Die Düngung mit N, P_2O_2 und K_2O wurde als NPK-Volldüngung alle drei Monate durchgeführt mit 14 g Pflanze^{-1} für die ersten sechs Monate nach der Pflanzung und anschließend mit 40 g Pflanze^{-1}.

Die Untersuchungen zeigten, dass die Höhe der Abaca-Pflanzen, die kumulierte Blattfläche sowie die Länge und der Umfang des Scheinstamms signifikant erhöht waren wenn die Intensität des Sonnenlichts auf 50 % reduziert war. Die Applikation des NPK-Volldüngers sowie eine Kombination von Düngung und Bewässerung verbesserten die Wuchsleistung von Abaca ebenfalls. Die

statistische Auswertung zeigte, dass Beschattung, NPK-Düngung und eine Kombination von Düngung und Bewässerung einen signifikant positiven Effekt ausübte auf Trockenmassebildung, Wachstumsrate, Blattflächenanteil und Netto-Assimilationsrate zwischen Keimlings- und Fahnenblattstadium. Darüber hinaus ergab sich für das Keimlingsstadium und das frühe vegetative Stadium ein signifikanter Einfluss einer hohen Beleuchtungsintensität (und/oder Temperatur) auf die Verteilung der Biomasse und der NPK-Nährstoffe zwischen den Pflanzenorganen und auch die differentielle Blattseneszenz im Fahnenblattstadium, wo Beschattung eine wichtige Rolle spielt, zeigte eine signifikante Beeinflussbarkeit. Die absorbierte NPK-Menge in den verschiedenen Pflanzenorganen variierte jedoch auch in Abhängigkeit vom Wachstum in den einzelnen Entwicklungsphasen und konnte hier jeweils durch Bewässerung und Düngung und die damit verbundene verbesserte Biomasseverteilung gesteigert werden.

In Bezug auf agronomische Parameter zeigten Abaca-Pflanzen, die einer 50 %igen Beschattung ausgesetzt waren, signifikant höhere Fasererträge als Pflanzen, die höheren Belichtungsintensitäten ausgesetzt waren, da bei starker Beschattung die Scheinstämme länger, größer und schwerer waren. Eine Kombination von Bewässerung und Düngung konnte den Faserertrag auf 141 % der Kontrolle steigern, jedoch war diese Steigerung geringer als der Effekt einer Beschattung, der den Faserertrag signifikant auf bis zu 265 % der Kontrolle steigerte. Dagegen zeigte die statistische Analyse, dass Beschattung, Bewässerung und Düngung keinen signifikanten Einfluss auf die Feinheit und die Reißfestigkeit der Fasern hatte.

Die beobachtete erhöhte Produktivität von Abaca als Reaktion auf Beschattung ist auf eine Vermeidung von Photoinhibition und photooxidativen Schäden zurückzuführen, welche vor allem im Keimlingsstadium und frühen vegetativen Stadium die Pflanzen bei vollem Sonnenlicht negativ beeinflussten. Die nachteiligen Auswirkungen der Photoinhibition auf die photosynthetische Kapazität von Abaca in vollem Sonnenlicht führten zu einer signifikanten Abnahme der Biomasseproduktion und -verteilung. Die durch die Pflanzenorgane absorbierte NPK-Menge erwies sich darüber hinaus als abhängig von der Belichtung, die zu photooxidativen Schäden im Keimlingsstadium und differentieller Blattseneszenz im Fahnenblattstadium führte. Dieser Zusammenhang hatte einen signifikanten Einfluss auf die Verteilung der Biomasse und der NPK-Nährstoffe zwischen den Pflanzenorganen. Dagegen steigerte eine NPK-Volldüngerapplikation zwar die Biomasseproduktion, hatte aber keinen Einfluss auf die Verteilung der Biomasse und der NPK-Nährstoffe. Um eine hohe Absorptionsrate für NPK-Nährstoffe in den Pflanzenorganen zu gewährleisten, wird eine Kombination von Bewässerung und Düngung in hohem Maße empfohlen. Dennoch zeigte die vorliegende Arbeit, dass auch eine Kombination beider Maßnahmen den positiven Effekt einer Beschattung auf das vegetative Wachstum, die physiologische Eigenschaften und die NPK-Absorption nicht aufwiegt oder egalisiert.

Des Weiteren entsprach die optimale Belichtung für eine optimale Ertragsleistung ohne die Faserqualität zu gefährden einer 50 %igen Beschattung. Wenn Abaca-Pflanzen allerdings bei diesem Beschattungsniveau angebaut werden, dann muss ein entsprechend angepasstes Bestandesmanagement implementiert werden um die notwendige Nährstoffversorgung zu gewährleisten (d.h. Düngung und/oder Kombination von Düngung und Bewässerung). Dieser Aspekt spiegelte sich vor allem auch in dem aufgezeigten signifikanten Effekt der Düngung auf das Wachstum von Abaca wider und dem Kombinationseffekt von Beschattung, Bewässerung und Düngung auf die äußeren und inneren Blattscheiden und den Gesamtfaserertrag.

CURRICULUM VITAE

Marlito M. Bande

PERSONAL DATA

Birth Date	:	March 24, 1971
Civil Status	:	Married
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Daughter	:	Gasa Mutya A. Bande
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FIELDS OF EXPERTISE

Agroecology, rainforestation, and community-based forest restoration, biodiversity protection and management

EDUCATION

2004	M.Sc. Agricultural Sciences, Food Security and Natural Resource Management in the Tropics and Subtropics, University of Hohenheim, Stuttgart, Germany Thesis: *Development of a sustainable abaca (Musa textilis Née) production in a diversified multi-strata agroecosystems in Leyte, Philippines*
1991	B.Sc. Agri-business (Management), Visayas State College of Agriculture, Baybay, Leyte, Philippines

EMPLOYMENT

Jan. 2012-present	Assistant Professor II, Institute of Tropical Ecology and Environmental Management, College of Forestry and Environmental Science, Visayas State University, Baybay, Leyte, Philippines
2004 -2011	Instructor I, Institute of Tropical Ecology, College of Forestry and Natural Resources, Visayas State University, Baybay, Leyte, Philippines
2000-2002	Science Research Assistant, Institute of Tropical Ecology, Visayas State University, Baybay, Leyte, Philippines

1995-1999	Community Organizer, ViSCA-gtz Applied Tropical Ecology Program, Visayas State College of Agriculture, Baybay, Leyte, Philippines
1992-1994	Process Documenter, Center for Social Research and Small Farmer Development (CSR-SFD), Visayas State College of Agriculture, Baybay, Leyte, Philippines

RELEVANT RESEARCH EXPERIENCE

- Project Leader, Community-based Forest Restoration and Biodiversity Protection and Management of Lowland Dipterocarp Forests in Silago, Southern Leyte, Philippines. Funding support from Philippine Tropical Forest Conservation Foundation. (January 2011 – December 2012)
- Study Leader, Habitat Restoration and Agroforestry Enhancement Using RF Technology through Community Participation in Brgy. Mantiquil, Siaton, Negros Oriental. Funding support from Environmental Leadership Training Initiative (ELTI) Program. (Feb. 2010 – Jan. 2011)
- Study Leader, Ecological Production of Abaca Fiber, Abaca Fiber Utilization in the Automotive Industry, DaimlerChrysler-DEG-PPP Project, VSU, Baybay, Leyte, Philippines. Funding support from DaimlerChrysler and DEG (2004-2008)
- Main Researcher, Physiological responses of abaca (*Musa textilis* Nèe) to light, water and nutrient availability in volcanic soils of Leyte Island, Philippines. Funding support from German Science Foundation (2008-2009)

RELEVANT INTERNATIONAL, NATIONAL AND LOCAL TRAININGS/ SEMINARS/CONFERENCES ATTENDED

- Understanding Forest Carbon Inventory and Monitoring Workshop and Sharing of Experiences by Communities and Assisting Organizations on April 19-24, 2010. NTFP-EP and 40 CoDe REDD partners, Imugan, Nueva Vizcaya, Philippines
- Mainstreaming Native Species-Based Forest Restoration Conference on July 15-16, 2010 at the University of the Philippines-Diliman, Quezon City, Philippines
- International Training on Soil Examination and Fertility Evaluation on August 16-18, 2006 at Visayas State University, Baybay, Leyte, Philippines
- Strategic Planning for the Conservation of Globally Threatened Species and their Habitats Workshop on November 29 –December 1, 2006 at Angelo King Center for Research and Environmental Management, Silliman University, Negros Oriental, Philippines
- 2nd Symposium on Long-Term Ecological and Biodiversity Research in the East Asia Region on October 25-26, 2006 at Central Mindanao University, Musuan, Bukidnon, Philippines
- 2nd South-South-North Fiber International Dialogue on March 4-5, 2005 at Visayas State University, Baybay, Leyte, Philippines. Sponsored by German Investment and Development Company (KfW Group), DaimlerChrysler, European Nature Heritage Fund, and University of Hohenheim, Germany, Universidade Federal do Para Belem, Para, Brazil and Visayas State University, Philippines
- Seminar on Management of Plant Genetic Resources in the 21st Century – Integration of Conservation and Utilization on February 7-10, 2005 at Visayas State University, Baybay, Leyte, Philippines

- National Workshop on Prospects for Reforestation in the Philippines on June 5 – 9, 2000 at Visayas State University, Baybay, Leyte, Philippines
- International Training Course on Vetiver Systems on November 19-30, 2000 at Chaipattana Foundation and Office of the Royal Development Projects, Bangkok, Thailand

RELEVANT INTERNATIONAL, NATIONAL AND LOCAL TRAININGS/ SEMINARS/CONFERENCES CONDUCTED

- National Rainforestation Trainers Training Workshop on April 22-27, 2009, May 18-22, 2009 and December 1-6, 2009 at Visayas State University, Baybay, Leyte, Philippines. Sponsored by Environmental Leadership Training Initiative (ELTI) Program, Yale University.
- 11th International Seminar and Workshop on Tropical Ecology on August 20 -25, 2006 at Visayas State University, Baybay, Leyte, Philippines. Sponsored by Martin Luther University, Germany and Visayas State University, Philippines.
- International Workshop on Tropical Ecology and Development Cooperation on August 14-26, 2005 at Visayas State University, Baybay, Leyte, Philippines. Sponsored by University of Hohenheim, Germany and Visayas State University, Philippines.
- 24th National Conference and Scientific Meeting of the Environmental Education Network of the Philippines, Inc. on May 24-26, 2005 at Western Philippines University, Puerto Princessa, Palawan, Philippines

SCIENTIFIC PUBLICATIONS

Bande, M.M., Grenz, J., Asio, V.B., Sauerborn, J., 2013. Fiber yield and quality of abaca (*Musa textilis*) grown under different shade conditions, water and nutrient management. Industrial Crops and Products 42(2013), 70-77

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Margarf, J., Milan, P.P., and M.J.M. Bande. 1999. Harvests from rainforestation: economic and cultural aspects of environmental farming. ViSCA-GTZ Applied Tropical Ecology Program.

SCHOLARSHIP AND RECOGNITION

- Eiselen MSc. Scholarship, Eiselen Foundation and Tropenzentrum, University of Hohenheim, Stuttgart, Germany from September 2002 – August 31, 2004
- German Research Foundation (DFG) PhD Dissertation financial support from September 2008 – August 2009

- Regional Outstanding Applied Research- Natural Resource Management Category, Visayas Consortium for Agricuture and Resources Program and Regional RDE Network for Agriculture and Fishery
- Regional Best Paper – Applied Category, Visayas Consortium for Agricuture and Resources Program and Regional RDE Network for Agriculture and Fishery
- Regional Outstanding Performance as Project Adviser- Life Science, Department of Education
- Regional Best Poster-Scientific Poster Presentation, NRCP Visayas Regional Cluster
- 2006 CHED Best HEI Research Program, Regional HEI Research Program, Commission on Higher Education

MEMBERSHIP IN PROFESSIONAL, SCIENTIFIC AND CIVIC SOCIETIES

- Rain Forest Restoration Initiative
- ViSCA Environmental Awareness Movement
- Terrestrial and Aquatic Restoration by Students Immersed in Environmental Reforms
- ViSCA Faculty Association

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