UNIVERSITY OF CAPE COAST

MORPHOLOGICAL CHARACTERIZATION AND POPULATION DYNAMICS OF *Cyperus rotundus* L. IN VEGETABLE FIELDS OF SOUTHERN GHANA

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BY

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Thesis submitted to the Department of Crop Science of the School of Agriculture, University of Cape Coast, in partial fulfillment of the requirements for the award of Doctor of Philosophy degree in Crop Science

JULY, 2016

DECLARATION

Candidate's Declaration

I hereby declare that this thesis is the result of my own original research and that no part of it has been presented for another degree in this university or elsewhere.

Candidate's Signature:.. Date:..........................

Name: Josiah Wilson Tachie-Menson

Supervisors' Declaration

We hereby declare that the preparation and presentation of the thesis were supervised in accordance with the guidelines on supervision of thesis laid down by the University of Cape Coast.

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ABSTRACT

Vegetable production in southern Ghana suffers grave setbacks from purple nutsedge infestation. Several attempts to identify effective and environmentally friendly management methods using the traditional weed research methods have so far not been successful. Hence, this study aimed at designing efficient and environmentally sound management methods by developing an ecological model of the population dynamics of purple nutsedge in vegetable fields. The study comprised three major phases: survey of the agronomic practices and prevalence of the weed in the four agro-ecological zones in the study area, morphological characterization of the weed and the development of an ecological model which was used in determining an appropriate management method. Purple nutsedge was reportedly present on the fields of more than 50 per cent of farmers interviewed and was said to be a problem all year round, especially in the wet season. The weed showed some level of morphological adaptation to agro-ecological conditions in the study area. The major factors which determined differences in purple nutsedge were photosynthetic structures (involucral bracts and leaves), plant height and leaf characteristics. On the whole, differences observed in the morphology of the weed were independent of the agro-ecological zones, despite the adaptations observed. The ecological model reflected purple nutsedge population dynamics at weekly intervals and the yield loss in cabbage (as a test crop) and hence was used to investigate various management options for the weed. It was clear that only an integrated weed management approach could effectively manage purple nutsedge. This approach should include an effective means of reducing the initial viable tuber density of the purple nutsedge.

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DEDICATION

In memory of my late dad, J. E. Tachie-Menson and my mentor in Weed Science, Prof A. G. Carson who passed on in the course of this study

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CHAPTER ONE

INTRODUCTION

Background to the Study

Weeds have been described as plants that are objectionable or interfere with the activities or welfare of man. In vegetable fields, weeds present grave biotic constraints to production. They compete with, and deprive the crops of basic resources such as moisture, nutrients, light and carbon dioxide. Additionally, they serve as alternative hosts and breeding points for other pests (such as insects and nematodes) and pathogens. Consequently, weeds reduce agricultural produce both in terms of quantity and quality.

Apart from the direct impact of weeds on vegetable crops, their control also presents additional cost to production. Weed control, in whichever way it is viewed, is a very expensive but important component of crop production which can increase the cost of production considerably. The difficulty in controlling weeds on vegetable fields has prompted the use of heavy doses of herbicides. This practice has presented a great deal of problems to the farmer, the consumer as well as the environment. Whiles the farmer exposes himself to the dangerous chemicals, which have both short and long term health effects; the environment suffers a great loss in biodiversity and disturbance of ecological balance. Consumers, on the other hand are exposed to heavy doses of systemic chemicals which could have long term effects on them. Weeds in vegetable fields even affect lifestyles of farming families. It is said that farmers in some developing countries deliberately have large families in order to provide source of labour for weed control on their fields (Akobundu, 1987). The ultimate impact of weeds on the vegetable crop production is thus, quite enormous; ranging from reduced quantity and quality of farm produce to increased cost of production and changed social lifestyles.

Most annual, biennial, and herbaceous perennial weed species, according to Grime (1979), are competitive ruderals, i.e. they have rapid early growth rates and competition between individual plants occurs before flowering. These weeds are well adapted and suited for competition with the crop and very often succeed in drastically reducing the growth rate and yield of the crops by rapidly increasing their population to gain early advantage over the crop. One important example of such weeds is the purple nutsedge (*Cyperus rotundus* Linn.)

Cyperus rotundus L. often known as purple nutsedge or less correctly as purple nutgrass, is a noxious, herbaceous, perennial weed of both the tropics and temperate regions, a member of the Cyperaceae family (Doll, 1994). The weed has an extensive underground system of rhizomes and tubers from which erect shoots emerge to a height of about 30cm and grows in nearly any soil type with any pH, soil moisture and organic matter. It is well suited to compete for nutrients, water and in early growth stage, for light due to its comparatively higher emergence and growth rate. While it is a weed of small stature, relative to most crops, it causes serious yield losses since it is a strong competitor for Nitrogen and can remove several kilograms of nutrients from the soil and store in its tubers and basal bulbs (Doll, 1994). In southern Ghana, the weed is known to be one of the most noxious weeds that has left farmers helpless in finding an economical and practical solution to it. The indigenous farmers refer to it as "shia me ndɔn num" which literally means "meet me at five o'clock", since according to the farmers, it re-emerges by five o'clock in the evening after it is weeded in the morning. While some farmers continue to spend huge sums of money on herbicides and manual labour to control this weed, others have abandoned vast arable lands to this weed (E. Hotor, personal communication, September 3, 2014).

The weed caused up to 40% reduction in crop yield in separate experiments (Cruz & Cardenas, 1974; Leihner & Lopez, 1980). The rhizome tip can penetrate the underground structures of crops such as roots, reducing their market value and also lower the starch contents of crops such as cassava. The weed is also known to have allelopathic properties whereby chemicals are produced to inhibit the growth of other plants in its vicinity. The purple nutsedge is found in more countries, regions and localities of the world than any other weed and was actually described as the world's worst weed by Holm, Plucknett, Pancho, and Herberger (1977), and continues to present serious difficulties to vegetable crop production in southern Ghana.

Vegetable crops are defined as herbaceous species grown for human consumption in which the edible portions consist of leaves, roots, hypocotyls, stems, petioles, and flower buds (Shannon & Grieve, 1999). Their classification is based on the plant part used as food and includes tomatoes, peppers okro (fruit vegetables); carrot, beetroot and swede (root vegetables) and cabbage, lettuce, cauliflower (leafy vegetables). They form an important part of most Ghanaian diets. Vegetables generally contain varying proportions of vitamins such as Vitamin A, Vitamin K and Vitamin B6; provitamins, dietary minerals, carbohydrates and some amounts of protein and fat, (Gruda, 2005). They are also known to contain a great variety of other phytochemicals, some of which have been claimed to have antioxidant, antibacterial, antifungal, antiviral and anticarcinogenic properties . Some vegetables also have high amounts of fibre, important for gastrointestinal functioning and other important nutrients necessary for healthy hair and skin as well. Thus consumption of vegetables has, over the past few years, become the campaign message for most health advocacies.

The call for increased consumption of vegetables may however not yield the desired result due to the numerous challenges faced by the vegetable production industry in Ghana. Vegetables, by the succulent nature, are highly susceptible to pests and diseases, both on the field and in storage. This results in huge losses incurred through the various stages of the production chain. William and Warren (1975) reported the following crop yield losses due to purple nutsedge competition as garlic 89%; okra 62%; two carrot cultivars, 'Kuroda' and 'Nantes' 39% and 50%, respectively; green bean 41%; cucumber 43%; cabbage 35%; and tomato 53%.

Problem Statement

Management of the purple nutsedge is obviously a very difficult task and has remained a major puzzle for vegetable farmers to date. The difficulty in the management of purple nutsedge is due to a number of reasons including its ability to tolerate a wide range of environmental conditions, ability of its tubers to remain dormant for several years, its rapid and prolific shoot production and its high tolerance to herbicides (William, 1976).

Intensive tillage, the most common weed management operation in southern Ghana, often, rather results in higher population of this nutsedge since it breaks the apical dominance of tuber chains and the dormancy of buds on individual tubers (Doll, 1994). The sedge therefore sprouts soon after weeding, making production very much labour intensive and expensive. The use of herbicides has shown some encouraging results. Glyphosate and 2, 4-D are known to be effective but can only suppress the weed for up to 40 days (Doll, 1994). A single application of the herbicide however cannot effectively manage the weed. This demands repeated applications of heavy doses of the herbicide, a practice that is environmentally unfriendly. The difficulty in managing the weed is even much more pronounced in organic vegetable farms where no herbicides are used.

Coupled with the difficulty in managing the weed, is the fact that there appears to be different biotypes of the weed at different locations (Willis, 1988). These biotypes may respond differently to different management programs, thus a management program that works for one biotype may not necessarily work for another biotype. Design of management programs should therefore consider the variations.

Consequently, there is an urgent need for a solution to this weed. Successful management of this weed requires an in-depth understanding of its population dynamics, biology and ecology, and how weed management methods impact on its population dynamics.

Traditional weed research methods which concentrate on the weed-killing power of various chemical and mechanical controls, and issues such as optimum time of application, (Cousens & Mortimer, 1995) have not yielded any conclusive result in the search for an effective and environmentally friendly management method for the weed. However, according to Kriticos

(1996) wide range of ecological models and modelling options applicable to weed management are now available. These models, if employed, will help in the design of more efficient and environmentally sound management methods for this weed.

Purpose of the Study

This study thus sought first, to assess the prevalence and variations in *Cyperus rotundus* L. in vegetable fields of southern Ghana and then to develop an ecological model of the population dynamics (of the most prevalent biotype) of the weed in the vegetable fields to help design efficient and environmentally sound management methods for the weed.

Specific objectives:

- To gather baseline information on the prevalence and methods of management of *C. rotundus* in southern Ghana
- To determine the relationship between some cultural practices and environmental (soil and climatic) factors on one hand and the prevalence of *C. rotundus* on the other hand
- To characterize *C. rotundus* germplasm collected from various locations across southern Ghana using morphological traits
- To develop an ecological model of the population dynamics of *C. rotundus* in the vegetable fields
- To test and validate the model empirically
- To utilize model to investigate various weed control measures and impact on vegetable yield

Significance of the Study

The model to be developed will take into consideration the biology and population dynamics of different collections of the weed from various parts of the study area (southern Ghana) and look at the effect of some factors such as amount of light, moisture, weed control efficiency, intra and inter-specific competition and initial density of tubers on the population dynamics of the weed. This will help identify a more reliable and effective but environmentally sound way of controlling the weed. Such an approach will be of great use to vegetable farmers who have either had to abandon vast lands to the weed or have had to use heavy doses of herbicides at very high cost in their quest to control the weed. The environment will as well be protected from such unfriendly practices.

Study Approach

The study began with an analysis of the system to be modelled – *Cyperus rotundus* in vegetable fields of southern Ghana – which led to the identification of the problem and the setting of objectives for the study. Literature reviews were conducted to enhance understanding of the system and to ensure that the biology of the weed was represented as accurately as possible in the model. Information was also gathered from interviews with vegetable farmers in the study area and from field surveys to provide a clearer understanding of the system. The information gathered, together with the results from various experiments gathered were used to formulate the model. The model, having been tested and analysed, was used to develop guidelines for management of the *Cyperus rotundus* in vegetable fields in the study area.

The approach followed is graphically presented in Figure 1.

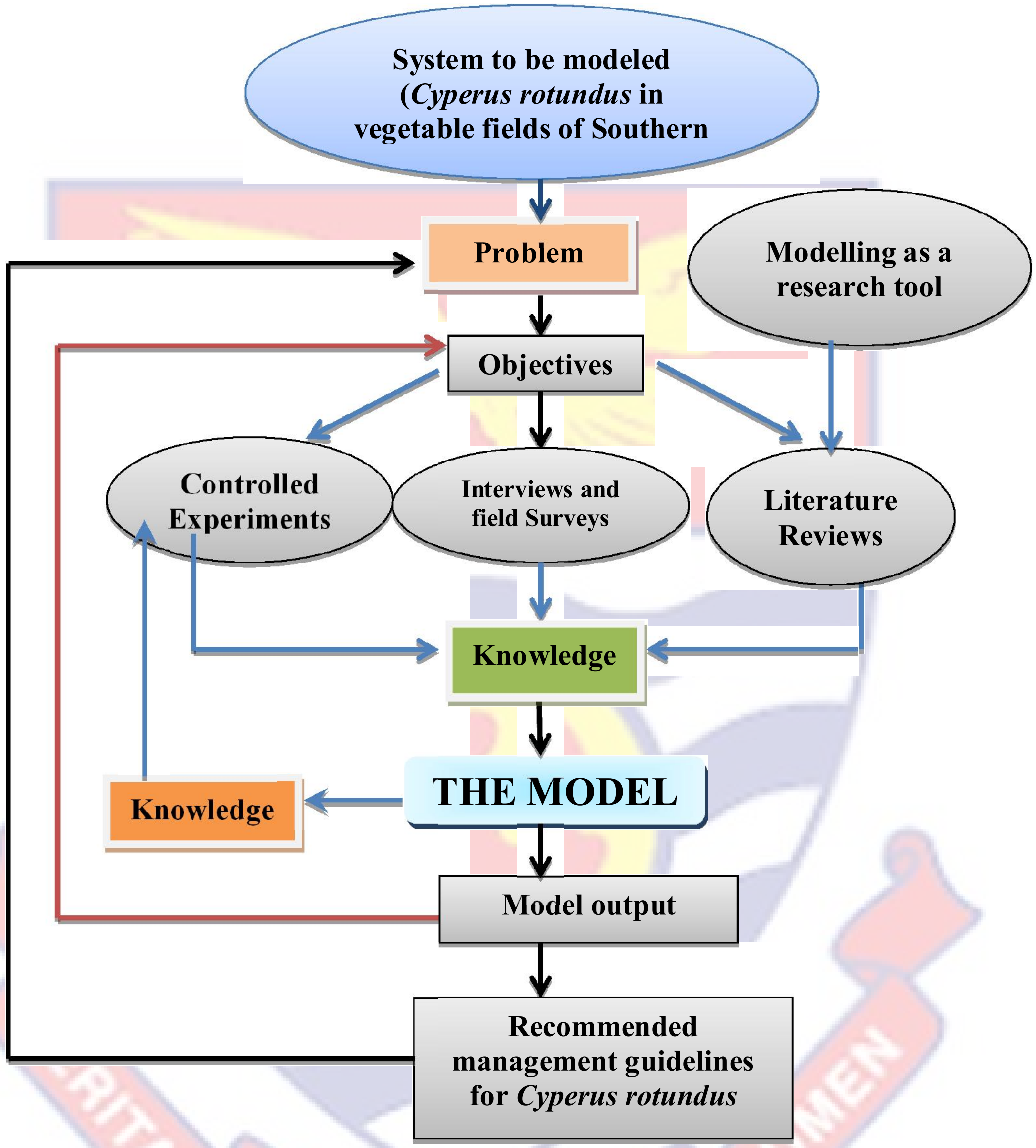


Figure 1: Diagrammatic representation of the approach of the study

CHAPTER TWO

LITERATURE REVIEW

Taxonomy, Origin and Distribution of *Cyperus rotundus*

Purple nutsedge (*Cyperus rotundus* L.) botanically belongs to the class Angiospermae, subclass Monocotyledoneae, order Cyperales, and family Cyperaceae (Leihner, Doll, & Fuentes de Piedrahita, 1984; Stoller & Sweet, 1987). Members of the family Cyperaceae (sedges) resemble those of the Gramineae (grass family) but are distinguished by their three-ranked leaves with one-third phyllotaxy. They are also characterised by leaves with closed leaf sheaths, solid stems, and the absence of ligules, with each flower sub-tended by a single glume or scale (Schonbeck, 2013). According to Stoller and Sweet (1987), the family Cyperaceae consists of approximately 3000 species of which only 220, including the purple nutsedge, are identified as weeds. Together with about 42% of these weeds, the purple nutsedge is classified under the genus *Cyperus*, (Bendixen & Nandihalli, 1987; Riemens, van der Weide, & Runia, 2008) and the species *rotundus*.

The origin of the purple nutsedge is unclear. While the United States Department of Agriculture [USDA] and Natural Resource Conservation Service [NRSC] (2000) report that it is native to India from where it was introduced to other parts of the world, Schonbeck (2015) believes the weed is native to the whole of Eurasia, whereas Parsons and Cuthbertson (1992) also reports its origin as been more widespread, including northern and eastern

Australia. At present, the most widely accepted distribution range considers this species as native to the tropical and subtropical Old World, principally Africa and Eurasia (Govaerts, 2014; United States Department of Agriculture & Agricultural Research Service, 2014).

Its distribution, like other plant species, is a function of ecological amplitude or genetic diversity and dissemination (Bendixen & Nandihalli, 1987). Bendixen and Nandihalli indicated that temperature and moisture are the two dominant limiting factors determining the distribution of the purple nutsedge, making it is a problem weed in the tropical and warm temperate countries since it prefers such wet places with high temperatures. The declaration of the purple nutsedge as the world's worst by Holm et al. (1977) was based on the number of countries where it was reported as a serious, principal, or common weed; with competition as the major factor determining its weediness. They concluded that the weed was found in more countries, regions and localities of the world than any other weed. The weed has since been reported to be serious in 52 countries including Ghana, Tunisia, South Africa (all in Africa), the United States of America, Mexico, Jamaica (North and Central America), Argentina, Brazil, Venezuela (South America), Japan, Sri Lanka, Philippines (Asia), and Italy, Portugal, Yugoslavia (Europe)(Bendixen & Nandihalli, 1987). It is also reported to be a principal weed in 18 countries, common in 4 countries and present in 17 other countries; giving a total of 91 countries across the globe (Bendixen & Nandihalli, 1987).

Morphology of *Cyperus rotundus*

The morphology of the purple nutsedge is a heavily discussed area. The weed is a perennial sedge which develops as a series of shoots having an extensive underground network of tubers, borne in chains of 2 – 6 or more on thin wiry rhizomes, and basal bulbs from which fibrous roots, and the erect shoots emerge up to about 30cm high (Doll, 1994; Schonbeck, 2015).

The tubers are condensed underground stems consisting of rhizomatous tissues with numerous lateral buds and a terminal bud, and are covered with scale leaves. They are irregularly shaped, progressively change in colour with maturity from white through light brownish colour to black and possess an acrid smell and taste (Akobundu & Agyarkwa, 1998; Stoller & Sweet, 1987). They are spaced approximately 5 to 25cm apart and serve as the primary source of infestation (Doll, 1994; Schonbeck, 2015; Stoller & Sweet, 1987).

Basal bulbs, according to Stoller and Sweet (1987), are the primary site for prolific vegetative growth because they possess the meristems for leaves, rhizomes, roots and flower stalks. Each basal bulb consists of a section of stem (rhizome) with compacted internodes containing meristems for roots, secondary rhizomes leaves and the flower stalk. They are similar to tubers in appearance and sprouting characteristics. They are reported to fuse with tubers to form perennial propagules with large amount of starch (Stoller & Sweet, 1987). They usually form near the soil surface (mostly within 8cm from soil surface) but may be as deep as 20cm.

Roots and rhizomes arise from the base of the basal bulb. The rhizomes are initially white and fleshy with scaly leaves and then become fibrous wiry, and very dark brown with age. They initially grow from 1 to 30cm horizontally and then turn either upward or downward, or may even continue horizontally (Doll, 1994; United States Department of Agriculture &

Natural Resources Conservation Service, 2000). Those which grow upward reach the soil surface and enlarge to form the basal bulb that produces new aerial shoots. The rhizomes that grow downward or continue horizontally remain underground and form tubers and may continue to form chains of tubers (Doll, 1994).

The aerial part of the purple nutsedge comprise a pseudostem with tightly clasping leaf-sheaths and a rosette of leaves arising from the short closely packed internodes (Akobundu & Agyarkwa, 1998). The leaves, which have three ranked leaf blades arising from or near the base of the plant, vary in number from 6-14 and are about half the length of the culm. They are mostly dark-green, shiny, narrow and grass-like and ranging from 5-12mm in width to 50cm in length with a prominent channel in cross section and tubular and membranous leaf sheaths.

In a mature plant, the culm (an elongated terminal internode) bears an umbel-like inflorescence consisting of an umbel of spikes (Akobundu & Agyarkwa, 1998). The upright culm is triangular in cross-section, usually taller than the foliage (about 10 to 50cm tall), and bears two to four small terminal leaf-like bracts which subtend the umbel-like inflorescence. These bracts are usually shorter than the longest spikes.

The inflorescence is composed of loose, purple brown spikes, some of which are sessile and others are borne on stalks. The stalks (also referred to as rays or rachilla) are unequal in length and usually 3 to 9 in number and bear 3-10 spikelets. Spikelets are flattened and linear ranging from 10 to 30mm in length and generally dark reddish, purple or reddish brown in colour. Each of the 20 or so florets in a spikelet is subtended by a keeled scale (glumes) 2-

5mm long with a green mid vein and a membranous margin. The flowers are bisexual each with three stamens and a pistil bearing three stigmas. Fruits, although rarely produced, consists of a three-angled achene (nutlet) (United States Department of Agriculture & Natural Resources Conservation Service, 2000).

Life Cycle of *Cyperus rotundus*

According to Schonbeck (2015), purple nutsedge initiates its life cycle almost entirely from tubers, as viable seeds rarely occur in the species. It also reported that seed production in purple nutsedge is variable and in most cases viability is low (Anonymous, n.d.). Seedling vigour is also observed to be poor, hence, seeds are considered to be unimportant to the reproductive capabilities of this plant. Reproduction is mainly by tubers. Each tuber has a number of small buds that form new plants. However the tubers lie dormant in the soil until stimulated to sprout. Soil warming is known to be the major sprouting stimulus in the temperate regions, while soil moistening stimulates sprouting in tropical regions (Horowitz, 1972b; Stoller, 1981; Stoller & Sweet, 1987).

Primary sprouting in purple nutsedge involves the elongation of a sharp pointed rhizome from the tuber bud, which grows toward the soil surface (exhibiting negative geotropism), then forms the subterranean basal bulb in response to light and diurnal temperature fluctuations which are the principal factors that stimulate the formation of basal bulbs on the rhizome under the soil surface (Schonbeck, 2015; Stoller & Sweet, 1987; Stoller & Woolley, 1983). The rhizome extends mostly by internode elongation until the basal bulb is initiated. Bulbs develop fibrous roots systems that may extend about 1m deep to the soil profile (Holm et al., 1977). Leaves then originate at the bulb from a plicate, triangular fascicle, beginning with the outermost leaf. The fascicle terminates under appropriate growth conditions, in a seed bearing rachis (Jansen, 1971; Stoller & Sweet, 1987; Willis, Hoagland, & Paul, 1980). The leaves extend below the soil surface to the basal bulb. Each successive, photosynthetically active leaf tends to be longer than the previous leaf in early shoot development (Jansen, 1971; Stoller & Sweet, 1987). Parent tubers remain attached to the plant throughout the season, and the plant may derive food from tubers in times of stress (Hammerton, 1974; Stoller, Nema, & Bhan, 1972; Stoller & Sweet, 1987)

According to Schonbeck (2015) and Stoller and Sweet (1987), secondary rhizomes radiate horizontally from the basal bulb two to three weeks after the emergence of the primary shoot. In the early growth stages, the rhizome tips turn upward, differentiating into secondary basal bulbs similar to the primary basal bulb. The secondary bulbs also produce further shoots, rhizomes, and flower stalks similar to those for the primary bulbs; and subsequent development of tertiary and higher order bulbs forms the complex system of subterranean, vegetative growth. In an open field without crop interference, a single tuber can proliferate into a dense stand of shoots covering several square meters in a single season (Hauser, 1962a, 1962b; Stoller & Sweet, 1987; Tumbleson & Kommedahl, 1961). Rapid vegetative proliferation occurs as conditions permit until tuberization predominates.

Purple nutsedge, according to Schonbeck (2015), usually flowers about 7–8 weeks after emergence, although flowering can occur as early as 3 weeks.

Stoller and Sweet (1987) also said that flowering is erratic among purple nutsedge populations and may not flower after growth for a cropping season. They indicated that the stimulant for flowering in purple nutsedge is not clearly identified.

New tubers begin to form at about the time of flowering. After flowering, purple nutsedge undergoes a marked shift from aboveground to belowground development, so that tubers continue to form for several weeks after shoot growth ceases (Schonbeck, 2015). Tuberization can begin within 17 days after shoot emergence (Hammerton, 1974; Stoller & Sweet, 1987) but dormant tubers are not found until about eight weeks after emergence (Hauser, 1962a; Stoller & Sweet, 1987). In temperate latitudes, tuber formation is triggered and accelerated by shortening daylength while above-ground growth rates decline. This cycle corresponds with the seasons, as tuber formation begins in late summer when photoperiods become shorter (Hauser, 1962a; Jordan-Molero & Stoller, 1978; Riemens et al., 2008). In the tropical climates, tuberization occurs all year round (Hammerton, 1975; Horowitz, 1972b; Stoller & Sweet, 1987). This may be in response to excess carbohydrate regulated by growth substances, photoperiod and temperature. By the time tuberization occurs, the plant complex would usually include many aerial shoots interconnected by rhizomes that are capable of diverting resources into tubers (Garg, Bendixen, & Anderson, 1967; Hammerton, 1975; Stoller & Sweet, 1987). Tuber production in the field can be very large; in temperate areas up to hundreds per plant and in tropical areas, up to thousands (Naber & Rotteveel, 1986) and an average of approximately one tuber per day per plant for the first 90 to 140 days, translating into a huge tuber population in a short time (Doll, 1994). Groenendael and Habekotté (1988) indicated that a tuber can produce up to 17000 tubers in one growing season in tropical and subtropical regions but in temperate zones, a tuber produces on average 500-600 tubers. When purple nutsedge is cultured in fields without interference from other plants, they can produce 10 to 30 million tubers per hectare in a season (Hauser, 1962a; Horowitz, 1972b; Riemens et al., 2008) after which tuber population seems to stabilize or decrease slightly (Stoller & Sweet, 1987; Stoller, Wax, & Slife, 1979). However, when the weed grows with crops, shading reduces tuber production (Jordan-Molero & Stoller, 1978; Keeley & Thullen, 1978; Stoller & Sweet, 1987). In a study by Stoller et al. (1979) involving continuous cropping of corn without adequate nutsedge control, tuber densities increased rapidly in the first season; then remained at about 1000 tubers/m^2 for the next 3 years, indicating that perhaps the rate of tuber production equals the rate of tuber decay at the point of equilibrium (Stoller & Sweet, 1987). In another trial in Georgia, purple nutsedge developed 5.38 metric tonnes above ground biomass and 9.41 metric tonnes below ground dry weight per hectare by 12 weeks (Hauser, 1962a) after which active foliar growth diminished while tuber formation accelerated. By 20 weeks, shoot biomass was 7.38 metric tonnes per hectare while below ground biomass reached 12 metric tonnes per hectare.

Effect of some agro-ecological factors on life cycle of *Cyperus rotundus*

The major climatic factors that determine the life cycle of the purple nutsedge include temperature, moisture, photoperiod and light intensity. These affect various stages of the life cycle including dormancy and sprouting, shoot emergence and proliferation, flowering and tuberization. Other factors such as soil properties, initial tuber density and the depth of burial, are also known to affect the life cycle of this weed.

Effect of temperature on life cycle of *Cyperus rotundus*

Due to apical dominance and bud dormancy, tubers can remain in soil for extended periods of up to 10 years before sprouting (Schonbeck, 2015; Stoller & Sweet, 1987). As reported by Horowitz (1972), soil warming is considered the major sprouting stimulus in temperate climates, while soil moistening is a sprouting stimulus in tropical conditions. Tuber dormancy is broken by high temperature and diurnal temperature fluctuations (Schonbeck, 2015). The minimum, optimum and maximum temperatures for sprouting of purple nutsedge are reported to be approximately 20, 30-35 and 45^0C respectively (Guehne, 1974; Horowitz, 1972a, 1992; Ueki, 1969). However, under alternate temperatures, some sprouting may occur at a temperature above 15^0C. This may explain partly why the purple nutsedge inhabits warmer climates. According to Horowitz (1992), tubers of purple nutsedge maintain their viability at the maximum temperatures recorded in most warm regions; thus, it is rather the minimum temperature which determines the seasonal development and geographical distribution of the species. Stoller (1973) also indicated that tubers lose their germinability when they are exposed to temperatures of 2^0C for three months. However, Shamsi, Al-Ali, and Hussain (1978) stated that chilling promotes tuber sprouting in purple nutsedge whereas Holm et al. (1977) reported that tubers are killed by freezing temperatures. Shoot and tuber formation are closely related to temperature changes. Plant growth is slow below 20^0C and most rapid at $26\text{-}35^0C$ (Bhardwaj & Verma, 1968; Hauser, 1962a; Horowitz, 1992; Mercado, 1979; Ueki, 1969). With decreasing temperatures the shoots wither. However, the vascular system of rhizomes remains intact after the aerial parts have decayed and the tubers formed on them overwinter (Horowitz, 1992).

Effect of moisture on life cycle of *Cyperus rotundus*

Purple nutsedge grows in a wide range of soil moisture including flooded soil (Horowitz, 1992; Ranade & Bums, 1925; Ueki, 1969). Horowitz (1992) observed that tubers sprout readily between 20% and 80% and most rapidly at 40% to 60% field capacity. He stated that desiccation may interact with temperature in affecting tuber longevity especially at intermediate temperatures . The impact of cold and desiccation on tuber longevity is a significant factor in tuber ecology. Desiccation and extremes of temperature can kill purple nutsedge tubers (Stoller & Sweet, 1987). Horowitz reported that drying tubers from their natural state of between 55% and 85% moisture content to below 15% will cause loss of germinability or even kill them, and intermediate moisture content will result in reduced viability (Horowitz, 1992), Stoller and Sweet added that the time required to reach this critical moisture level apparently may not be important, even though it may take between 7 and 14 days of field drying under full sunlight to kill the tubers .

Effect of light intensity and duration on life cycle of *Cyperus rotundus*

Temperature also interacts with light to affect the purple nutsedge. The weed possesses the C4 dicarboxylic acid photosynthetic pathway which allows plants to assimilate CO_2 efficiently at high temperatures and light intensities (Horowitz, 1992; Stoller & Sweet, 1987; Willis, 1987). This contributes to its ability to grow and spread rapidly in hot weather and high light levels. The shoot and tuber production of the purple nutsedge is correlated with the intensity of photosynthetically active radiation, making it shade intolerant (Schonbeck, 2015). Shading greatly reduces the number and size of tubers produced, (Schonbeck, 2015) although tubers remain viable and send up new shoots when canopy is removed (Holm et al., 1977). Neutral shade (white cheesecloth) that reduced incident light by 20% reduced purple nutsedge growth (dry weight accumulation) by 25%, whereas 60% shade cut aboveground dry weight by 80% and tuber dry weight 97% (Santos, Morales-Payan, Stall, Bewick, & Shilling, 1997a). Thus when crops compete with purple nutsedge for light, they exert an interfering effect. Rhizome initiation and development and tuber formation in purple nutsedge are controlled photoperiodically. Photoperiods longer than 12 hours promote rhizome development and shoot production, while shorter photoperiods promotes tuber formation (Bendixen & Nandihalli, 1987). Horowitz (1972b) however reports that natural daylength has no effect on tuberization in purple nutsedge.

Effect of some soil characteristics on life cycle of *Cyperus rotundus*

Purple nutsedge can grow in nearly any soil type, pH, level of soil moisture and organic matter (Doll, 1994), and is significantly improved by different soil nutrients such as nitrogen, phosphorus and potassium (Iqbal, Hussain, Ali, & Javaid, 2012). Lousada et al. (2013) confirmed that purple nutsedge growth correlates positively with the soil nutrients. However, while indicating similar relationship (positive correlation) with clay contents of soil, they reported a negative correlation with pH, and high sand content in sugarcane fields of Rio de Janeiro. This disagreement (on the correlation between pH and soil type on one hand and the growth of the purple nutsedge on the other hand) however may be as result of ecotypic variation in the weed species as indicated by Stoller and Sweet (1987) and Pena-Fronteras et al. (2008) which makes it adapt to and thrive in any kind of soil. Doll (1994) also indicated that the weed does not tolerate salty soils.

Effect of Depth of Burial and Extent of Contact with Soil of the Sprouting of *Cyperus rotundus* Tubers

Haizel and Bennett-Lartey (1986) observed that provided a tuber is buried completely, its chance of sprouting was high irrespective of the depth at which it occurred. This was confirmed by Chase, Sinclair, and Locascio (1999) who also indicated however that the sprouting is better for tubers buried deeper when soil is solarised with low-density polythene (LDPE) clear film. Tubers lying on soil surface with minimum contact with soil however had very poor chances of sprouting and survival was as well poor (Haizel & Bennett-Lartey, 1986).

Effect of tuber density (Intra-specific competition):

According to Iqbal et al. (2012) planting density significantly affects different growth and tuber characteristics of purple nutsedge. They reported that shoot density per pot was significantly increased (78–151%) by increasing number of tubers per pot as compared to the planting of 5 tubers per pot. Shoot length, shoot biomass, underground biomass, number of tubers produced per pot and tubers weight were significantly increased up to the planting of 15 tubers per pot then decreased by planting 20 tubers per pot. Planting higher densities of tubers decreased per tuber weight up to 93%. He concluded that the intraspecific competition within purple nutsedge is less up to a certain limit but higher planting density limits the plant and tuber growth.

Variations in *Cyperus rotundus*

Variations have been repeatedly reported in purple nutsedge (Pena-Fronteras et al., 2008; Stoller & Sweet, 1987; Willis, 1988). This prompted the description of various subspecies even though they are hardly recognized in literature. Haines and Lye (1983) described four subspecies from East Africa, *rotundus, merkeri, taylorii and tuberosus*. Variations in *C. rotundus* has also led to description of ecotypes, such as those based on glume colour (Ranade & Bums, 1925), morphotypes (Willis, 1988) and chemotypes, such as those from Japan and China based on sesquiterpenes in tubers (Komai & Ueki, 1981).

Variability appears in almost every morphological and biological characteristic, including tuber dormancy and longevity, rhizome and tuber development, flowering and responses to herbicides. This is particularly pronounced when locations are involved (Stoller & Sweet, 1987). Willis (1988) reported various reproductive and morphological differences in purple nutsedge collections from 13 states within continental United States and from 21 other locations around the world. He found differences in the number of shoots produced from single tubers, the number of leaves per shoot, and the length and width of leaves. Differences were also found with respect to flowering length of culms supporting the inflorescence, and number, length, and width of involucral bracts at the apex of the culms. Variations also occurred in the flower parts, including the number and length of rachises and the length of rachillae and spikelets. There were differences in the growth patterns of the leaves, with some collections having leaves mostly erect and others having leaves lie more closely to the ground. The colour of the leaves varied between light and dark green, and the colour of the inflorescence varied between light and dark purplish-brown.

Pena-Fronteras et al. (2008) investigated the ability of purple nutsedge to tolerate both flooded soil conditions and upland conditions in the Philippines and reported the existence of adapted ecotypes. They reported that the lowland ecotype had much larger tubers than the upland ecotype. Again, prior to germination, the amylase activity and total non-structural carbohydrate content in the form of soluble sugars were greater in the tubers of lowland plants than in those of upland ecotypes of the purple nutsedge.

Willis (1988) concluded that although morphological descriptions of purple nutsedge have been reported widely, there are purple nutsedge populations with significantly different morphological characteristics from those previously reported and these variations may influence its competiveness in cropping situations and also may affect its response different methods of control adding that the different biotypes of purple nutsedge can be positively identified in many different geographical locations around the world.

Effect of *Cyperus rotundus* on crops

The impact of the purple nutsedge on crops is exhibited through competition with crops for nutrients, moisture and light; direct damage caused to crops, and the inhibition of the growth and yield crops in its immediate vicinity through the release of chemicals (allelopathy).

The weed is well suited to compete for nutrients, water and in early growth stages, for light because it emerges and grows more rapidly than most crops (Doll, 1994). It competes strongly for nitrogen and can deprive the crops of several kilograms of nutrients which it stores in its tubers (Bhardwaj & Verma, 1968), thereby reducing the growth and yield of the crop. William and Warren (1975) reported that crop losses due to purple nutsedge competition in Brazil for a number of vegetables ranged from 35% to 89% with the critical periods of purple nutsedge competition occuring between 3 and 13 weeks for garlic; 3 and 7 weeks for okra, cucumber and carrot, 3 and 5 weeks for tomato and approximately 4 weeks for cabbage and green bean.

Nitrogen seems to significantly, improve the competitive ability of the weed. Okafor and De Datta (1975) observed that competition for moisture and light was greatly enhanced with added nitrogen in field trials with upland and lowland rice in the Philippines. Competition experiments between purple nutsedge and various crops showed that both root and shoot competition (for light and nutrient) from purple nutsedge affect the growth and development of the crops. Root competition however, was seen to be relatively more important than shoot competition (Riemens et al., 2008; Tuor & Froud-Williams, 2002).

The purple nutsedge can also reduce the quality of roots crops like sweet potato and cassava, tuber crops like potatoes and onion bulbs. The rhizome tip can penetrate these underground structures, reducing their market value and also lowering the starch content of cassava (Doll, 1994; Leihner & Lopez, 1980; Schonbeck, 2013). The weed also affects crop growth by releasing allelopathic substances (Drost & Doll, 1980; Friedman & Horowitz, 1971) and by hosting some diseases such as rust as well as plant parasitic nematodes.

Management of *Cyperus rotundus*

A number of measures have been proposed for the management of this weed, including both chemical and non-chemical methods. Each of these come with its own advantages and disadvantages, but successful management of this weed should take into consideration the growth habits, biology and ecology of the weed (Doll, 1994).

Competition and crop choice

Purple nutsedge is a C_4 species and therefore requires a good amount of light for optimum growth; hence crops well suited to compete for sunlight restrict the growth of this weed (Riemens et al., 2008; Rotteveel & Naber, 1988). Tall crops (1m or more in height) are thus more competitive with purple nutsedge than shorter ones. Again, fast growing crops soon outgrow the weed and hence require additional control measures for shorter periods after planting than slower growing crops. Similarly, adjusting the crop spacing to the narrowest practical width for each crop and the plant density to the highest practical level assures rapid shading and hence control of the weed (Doll, 1994).

Mowing

Brecke, Stephenson, and Bryan Unruh (2005) reported that the control of shoot biomass of purple nutsedge by mowing could lead to depletion in the total tuber number and tuber viability by reducing the carbohydrate reserves. Summerlin, Coble, and Yelverton (2000) also found that the length of the rhizomes, the number of tubers and the size of the tubers could be reduced by mowing grass 1 to 3 times per week. The mowing height was very important; mowing at a height of 1.3 cm readily affected nutsedges after 6 weeks, while mowing at a height of 3.8 cm affected nutsedge 9 weeks after the first mowing treatment (Brecke et al., 2005)

In a greenhouse experiment by Santos, Morales-Payan, Stall, Bewick, and Shilling (1997b) with four tuber fresh weight categories, (0.25, 0.50, 0.75 and 1g per tuber) planted, with primary shoots removed for the first time after six days after transplanting, the smaller tubers (0.25g and 0.50g) were unable to regrow and were depleted 30 days after planting. However, the larger tubers (0.75g and 1.00g) were able to recover. When the first removal took place at 12 days after transplanting, the smallest tubers (0.25g) were depleted after 42 days, whereas the other tubers were unaffected. No effect of tuber size was found when first removal was imposed at 18 days after planting or later. These results imply showed the dependence of the control efficiency on tuber weight (or size) and the timing of the removal of the shoots.

Soil tillage (Mechanical control)

Mechanical control, in spite of its wide use in the tropics, may affect the purple nutsedge either positively or negatively, depending on the prevailing conditions. With high soil moisture content, tillage practices promote the proliferation and spread of the weed (Riemens et al., 2008) by breaking the dormancy of viable tubers in the soil and serving as a mode of dispersal for the tubers (Doll, 1994). When conditions are dry, tillage operations contribute to a reduction of the tuber population by exposing them dessication and subsequent death, when the tubers are brought close to the soil surface (Leihner et al., 1984).

Soil solarisation

Soil solarisation is a method of increasing soil temperature in the field, usually with clear polyethylene mulch (Katan, Greenberber, Alon, & Grinstein, 1976; Miles, Kawabata, & Nishimoto, 2002). This practice has also been found to impact on purple nutsedge both positively (promote its proliferation) and negatively (serves as a control measure).

Miles et al. (2002) reported that five weeks of soil solarization with clear polyethylene film at Waimanalo, Hawaii which raised the mean soil temperature at 15-cm depth by 5.8^{0}C in spring, increased the final sprouting percentage in the field from 74 to 97% in spring and from 97 to 100% in summer. Locascio et al. (1999), however reported that soil solarisation for eight to ten weeks suppresses nutsedge infestation in strawberry fields in two locations: Quincy and Gainsville although at Gainsville, regrowth occurred when the mulch was cleared after soil solarization with black painted mulch.

Biological control

Classical biological weed control includes the strategy of augmenting an indigenous natural enemy (insects, fungi, bacteria, viruses, farm animals, etc.) to kill or to suppress the weed host by applying high inoculums pressure at an appropriate time (Phatak, Callaway, & Vavrina, 1987). This has been termed bioherbicide tactic (Templeton & Smith, 1977; Templeton, TeBeest, & Smith, 1979) or inundative biological control (Wapshere, 1979). Studies on, and the application of this approach dates back to 1795 when an insect, *Dactylopius ceylonicus* was introduced for drooping pricklypear control over a vast area (Goeden, 1978; Julien, 1982; Phatak et al., 1987; Rao, Ghani, Sankaran, & Mathur, 1971; Tyron, 1910). Phatak et al. (1987) listed a number of living organisms that were ever reported as natural enemies of purple nutsedge. The list included 132 insect species, 26 fungal species, 10 nematode species two bacteria and a virus species and some farm animals.

Biological control of purple nutsedge with insects

A number of the insects have been proposed as potential agents for nutsedge control. These include *Aleurocybothus* sp., *Antonia australis, Athesapeuta cyperi, Bactra minima minima, B. verutana, B. truculenta, B. venosana, Chorizococcus rostellum, Dercadothrips caespitis, Phenacoccus solani, Rhizoecusi cacticans, Shoenabius* sp., *Sphenophorus phoenicicensi* and *Puccinia canaliculata* (Phatak et al., 1987). Most of these however, have not been accepted as suitable for classical biological control because they could not sufficiently control the purple nutsedge, whereas others are also known to be vectors of various crop diseases (Riemens et al., 2008). Charudattan and DeLoach (1988) and Morales-Payan, Charudattan, and Stall (2005) also reported that approximately half of these insects are known to feed on crop plants making them pests of important crops, others were cannibalistic (Story & Robinson, 1979) and these attributes disqualify them as useful weed bio control agents.

Three moths, namely *Bactra verutana* Zeller, *B. minima* Meyrick and *B. venosana* Zeller, and one weevil, *Athesapeuta cyperi* Marshall, have been studied in detail (Frick, 1978) and have all proven to be adequately host-specific, yet none has proven to be effective as classical biological control agents (Phatak et al., 1987). For example *A. cyperi* was introduced to control purple nutsedge in Barbados in 1973, Cook Islands in 1971 and 1973, and Fiji and Tonga in 1971 but could not survive. Though it established in Hawaii following releases in 1925, it had negligible effect on the purple nutsedge. *B. minima* was also released in Cook Islands in 1973 and Fiji and Tonga in 1971 but could also not survive. In effect, attempts to control purple nutsedge with classical biological control have not been successful with these four insects tested at several locations (Phatak et al., 1987). *B. furfurana*, *B. lancealana*, *B. venosana* and *B. bactrana* were successful in partially defoliating purple nutsedge in Italy, but tubers were undamaged and the weed recovered (Trematerra & Ciampolini, 1989).

Biological control of purple nutsedge with fungi

According to Morales-Payan et al. (2005), fungi constitute the most abundant pathogens of purple nutsedge and have so far received more attention in the search for potential biological control agents than any other organism. They listed the fungi genera associated with purple nutsedge as *Alternaria*, *Ascochyta*, *Balansia*, *Cercospora*, *Chaetophoma*, *Cintractia*, *Claviceps*, *Cochliobulus*, *Corynespora*, *Curvularia*, *Dactylaria*, *Dreshclera*, *Duosporium*, *Entyloma*, *Fusarium*, *Macrophomina*, *Marasmius*, *Phaeotrichoconis*, *Pythium*, *Phyllosticta*, *Phytophthora*, *Puccinia*, *Rhizopus*, *Sclerotinia*, *Septoria*, *Tanatephorus*, and *Uredo*. Some of these have been evaluated as potential control agents whiles others have only been listed as been associated with the weed. Prominent genera among the potentials ones as reviewed by Morales-Payan et al. (2005) are further discussed.

***Balansia* spp.**

Some members of this genera were reported to cause inflorescence malformation and smut in purple nutsedge in the USA (Clay, 1986), the Dominican Republic (Morales-Payan, Charudattan, & Stall, 1998) and in Mexico (Carrión & Chacón, 1993). Stovall and Clay (1988) reported that purple nutsedge planted with *B. cyperi* produced fewer flowers and shoot biomass than non-inoculated plants. However, the inoculated also produced more tubers (though smaller) than disease-free ones; were less susceptible to *Fusarium oxysporum*, *Rhizoctonia solani* and *R. oryzae*, and less preferred by fall armyworms (*Spodoptera frugiperda*) which feeds of the weed. Such fungal antagonism would be counterproductive for weed suppression. Since the infection actually results in increased reproductive potential (more tubers produced) and repels other natural enemies, there would seem to be little benefit from using *B. cyperi* for purple nutsedge management.

***Curvularia* spp.**

Three species of *Curvularia* are reportedly pathogenic to purple nutsedge: *C. tuberculata, C. oryzae and C. lunata* (de Luna, Watson, & Paulitz, 1998, 2002). However, *C. tuberculata* and *C. oryzae* are known pathogens of some rice cultivars. Shelby and Bewick (1991) investigated the efficacy of *C. lunata* in the control of purple nutsedge in tomato, and reported that the pathogen produced typical disease symptoms on nutsedge, but the extent of control was not satisfactory. Moreover, *C. lunata* is known to cause a stem disease in cassava (Msikita, Yaninek, Ahounou, Baymai, & Fagbemissy, 1997), rice (Chu & Chen, 1973), which may be a cause of concern when the fungus is intended for use in those crops.

***Ascochyta* spp.**

Ascochyta cypericola has been reported to cause leaf blight in purple nutsedge (Upadhyay, Kenfield, & Strobel, 1991). The fungus is pathogenic to only plants in the genus *Cyperus* and disease severity in purple nutsedge was reported to be extensive. In addition, Stierle, Upadhayay, and Strobel (1991) reported that *A. cypericola* produced cyperine, a phytotoxin that may have potential as a natural herbicide (Dayan & Allen, 2000). *Ascochyta cyperiphthora* was found to cause leaf scorching in purple nutsedge in Brazil (Pomella & Barreto, 1997), but it efficacy for biocontrol is uncertain. Information on this genus and its phytotoxins for control of the purple nutsedge remains inadequate and will warrant further research.

***Puccinia* spp.**

Several species of the genus *Puccinia* reportedly attack nutsedge in the USA (Phatak, 1984), Brazil (Barreto & Evans, 1995), Panama (de la Cruz & Merayo, 1990; Esquivel, 1991), India (Bedi & Sokhi, 1994) and Dominican Republic (Morales-Payan et al., 1998) with the species *P. canaliculata* and *P romagnoliana* been the most widespread. Unfortunately, most purple nutsedge biotypes exhibit low susceptibility compared to other species of the genus *Cyperus*. In India, *Puccinia romagnoliana* was found causing rust to purple nutsedge. In field trial with this pathogen applied to purple nutsedge, the rust reduced plant fresh weight and dry weights by 64% and 56% respectively, and tuber number and weight were reduced by 34% and 83% respectively. Nutsedge plants between 2 and 4 weeks after emergence were the most susceptible in terms of growth reduction after being treated with *P. romagnoliana* (Bedi, Kaur, & Sokhi, 1995; Bedi & Sokhi, 1994). Results from (Dinoor, Boyle, Aust, & Eshed, 1994a; Dinoor, Ronen, Eshed, Kleifeld, & Zilberstaine, 1994b) support the finding of (Bedi et al., 1995). V. P. Gupta, Kumar, Mishra, Thiagarajan, and Datta (2002) showed that *P. romagnoliana* significantly reduced purple nutsedge shoot growth and tuber production in India. The major obstacles for working with *Puccinia* rusts seems to be the need to maintain a large amount of infected plants for mass-production of inoculums and the less susceptibility of the purple nutsedge to this pathogen.

***Cercospora* spp.**

Cercospora species have been reported to affect nutsedges in several countries of continental America. Gamboa and Vandermeer (1988) found an unidentified Cercospora species infecting purple nutsedge in Nicaragua. In that instance, disease severity was greater in purple nutsedge growing in maize and bean crops than in those growing alone which may be partially attributed to the higher relative humidity provided by the crop canopies. *Cercospora caricis* was reported to cause a foliar disease in purple nutsedge in southern Brazil (Barreto & Evans, 1995; Ribeiro, Mello, Furlanetto, Figueiredo, & Fontes, 1997). Genetic differences were however detected in this pathogen (Inglis et al., 2001) and this may have important implications on its virulence towards the host weed. Aly et al. (2001) proposed a biolistic system which could genetically transform *C. caricis*, to enhance its pathogenicity and efficacy for purple nutsedge control. This use of genetically modified organisms for weed control may however not be accepted by organic growers and consumers.

Studies on the host-plant relationship and the effect of *C. Caricis* on purple nutsedge as affected by weed age, inoculum application rate and dew period after application was conducted by Borges-Neto et al. (2000). They reported that the pathogen penetrates purple nutsedge leaves only through open stomata and that the weed was most susceptible between 3 to 4 weeks after emergence. The best results were obtained with 20g of fresh inoculum (mycelium) per litre followed by a dew period of 48-72 hours. Increasing the number of applications resulted in increased disease severity. The pathogen is also reported to produce the phytotoxin cercosporin which, however, is known to be host non-selective.

C. caricis has been extensively studied and there is ample information on its biology, epidermiology, effect surfactants, efficacy on purple nutsedge under greenhouse and field conditions. There are viable inoculum production models and its compatibility with several chemical pesticides is known. This fungus may be a likely candidate for commercial bioherbicide for purple nutsedge management.

***Dactylaria* spp.**

A prominent and widespread species of this genus, *Dactylaria higginsii* (formerly called *Pyricularia higginsii*), is reported to be a promising biological control agent (Barreto & Evans, 1995; de la Cruz & Merayo, 1990; Esquivel, 1991; Morales-Payan et al., 1998) for at least five species of

Cyperus including the purple nutsedge (Kadir & Charudattan, 1996). Typical symptoms of this fungus include dark brown oval-shaped leaf spots, which eventually coalesce and cause leaf blight. These symptoms are noticed 4 to 15 days after spraying the fungus on the weed canopy. Kadir, Charudattan, Stall, and Brecke (2000) found that increasing the number of applications and the spore concentration results in increased weed suppression. The efficacy of the fungus is however significantly influenced by environmental conditions. Under field and greenhouse conditions, temperature, dew period and relative humidity during periods of inoculation and disease progress proved to be important for disease progress. In the greenhouse, Kadir, Charudattan, and Berger (2000) found that a minimum dew period of 12 h at a 25 C temperature was necessary for *D. higginsii* to kill almost 100% of a population of young purple nutsedges, and that the dew period may be partially substituted by using selected humectants in the spray mixture. In the field, high relative humidity and temperatures between 25 and 30 C appear to favour the activity of the fungus.

Surfactants play an important role in *D. higginssi* efficacy for purple nutsedge control. In field and greenhouse experiments, the best results are usually found when spraying the potential bioherbicide with vegetable oils, as opposed to other surfactants (Morales-Payan, Charudattan, Stall, & DeValerio, 2003). Rosskopf, Yandoc, Kadir, and Charudattan (2003) applied *D. higginsii* on purple nutsedge-infested plots during the humid fallow season (summer) in Florida, and found that nutsedge suppression was comparable to that found in plots managed with glyphosate and disking. Thus, *D. higginsii* may be used for nutsedge population reduction prior to the autumn crop season as an alternative for glyphosate in organic and conventional cropping systems.

The percentage of *D. higginsii* spore germination was reduced when exposed to thiophanate, oxyfluorfen, glyphosate, sethoxydim, fosetyl-Al and dicofol, but spore germination percentage was equal or higher than control spores (treated with water) when exposed to cyromazine, diuron, imazapyr, nicotinic acid, mefenoxam and copper hydroxide (Yandoc, Rosskopf, & Charudattan, 2003).Thus, *D. higginsii* would be compatible with some agrichemicals, but not with others.

In effect, the use of bioherbicides for the control of purple nutsedge is still at its developing stages. It is unlikely that any single bioherbicide documented to date will provide the ultimate control of nutsedges much needed. However, documented research results show that several fungal species have the potential to be developed into bioherbicides that may play an important role in integrated nutsedge management strategies in conventional and organic production systems (Morales-Payan et al., 2005).

Chemical control of purple nutsedge

In spite of the recognized importance of the purple nutsedge the in world agriculture, and the much work done in the past on herbicide efficacy on this weed, relatively few chemical control alternatives are available (Doll, 1994). This is partly due to the fact that most of the herbicides such as methyl bromide, and Disodium methanearsonate (DSMA) that show good results are no more allowed and are not to be used for weed control, (Riemens et al., 2008).

Early reports on chemical control were published in the 1950's about the control with 2,4-D. Later reports dealt the use of Monosodium methanearsonate (MSMA), bentazon, thiocarbamates, the acid amines, triazines, uracils and fumigants, glyphosate and finally the imidazolinone and sulfonylurea herbicides (Cudney, 2003). Doll (1994) also listed a number of possible herbicides for the control of this weed. He however was quick to add that several of the herbicide labels for the products mentioned described their effect as "suppression" of the purple nutsedge rather than control. This was because length of control for most of these products was, at best, up to 40 days.

2, 4-Dichlorophenoxyacetic acid herbicides

2, 4-Dichlorophenoxyacetic acid, commonly called 2, 4-D is a widely used selective herbicide used to kill broadleaf weeds. It belongs to the phenoxy class of chemicals. It is a plant growth regulator and mimics the growth hormone, auxin. However unlike auxins, 2,4-D stays at high levels in plants tissues rather than fluctuating. This results in abnormal rapid cell growth which blocks and destroys the plant transport tissues and finally causes the death of the plant (Anonymous, 2004).

Hauser (1963) reported that the 2,4-D killed the purple nutsedge plant system only if the treatment begun within two weeks after emergence. Burr and Warren (1972), also reported that two application of 2,4-D reduced the weed's infestation but did not completely provide control of the weed. Standifer (1974) indicated that three applications of 2,4-D is required to kill an emerged purple nutsedge plant and their parent tubers. Ameena and George (2004) compared the efficacy of 2,4-D and glyphosate in controlling the purple nutsedge at various doses and reported their lowest dose of 1.5kg ai/ha gives complete shoot control up to six weeks after treatment with tuber dry weight also showing drastic reduction. Doll (1994) also reported that a relatively low cost strategy to reduce tuber population is the use repeated application of 2,4-D.

Monosodium methanearsonate

Monosodium methanearsonate (MSMA) is an organic arsenical, a class of herbicides that also includes DSMA, CAMA, cacodylic acid and its sodium salt. It is important to note that all products containing DSMA, CAMA, cacodylic acid and its sodium salt were banned in the United States as of September 2009 (Caulkins, 2009). MSMA is a broad spectrum herbicide used to control grasses and broadleaf weeds. It acts as a nucleic acid inhibitor.

Long, Allen, and Holt (1962) reported that repeated applications of MSMA for a 2-year period reduce the number of purple nutsedge tubers in Bermuda grass. This was confirmed by Hamilton (1971) who indicated that four to eight foliar applications of 5.6 to 16.8kg/ha MSMA in one year effectively control purple nutsedge. Widiger (1966) however suggested that the herbicidal efficacy of MSMA is partially dependent on weather conditions during and following the application but his suggestion was opposed partially by Keeley and Thullen (1971) who reported that the efficacy of the herbicide does not change with temperature between 13^0C and 29^0C

Thiocarbamates herbicides

The thiocarbamate herbicides belong to the group of S - thiocarbamate esters and include butylate, cycloate, EPTC, thiobencarb and trillate, pebulate,vernolate among others. They act as lipid synthesis inhibitors (Sprague, 2013).

Rincon and Warren (1978) evaluated five thiocarmate herbicides: butylate (S-ethyl diisobutyl-thiocarbamate), EPTC (S-ethyl dipropylthiocarbamate), molinate (S-ethyl-hexahydro-1H-azepine-1-carbothioate), pebulate (S-propyl butyl-ethyl-thiocarbamate), and vernolate (S-propyl dipropylthiocarbamate) in greenhouses at doses of 0.5 to 5kg/ha incorporated 6cm deep in a silt loam with purple nutsedge tubers planted at 5cm deep. They reported that the most effective reduction in the number of sprout above ground was given by butylate, EPTC and vernolate. These were followed by pebulate and molinate. Persistence of the herbicides was directly related to level of initial activity. They indicated that all the thiocarbamates stimulated the number of sprouts produced per nondormant tuber. These sprouts were however abnormal and did not reach the soil surface. The number of rhizomes produced from the basal bulbs was also reduced with all the thiocarbamates used.

Paraquat

Paraquat (1,1'-dimethyl-4,4'-bipyridiniumion) is one of the most widely used herbicides in the world. It is a non-selective contact herbicide used for the control of weeds in vegetable rows (http://www.pan-uk.org/pestnews/Actives/paraquat.htm). It belongs to the Bypyridylium class of chemicals and hence acts as a Photosystem I electron diverter (Sprague, 2013).

Paraquat damages nutsedge foliage but regrowth is rapid and tuber production is not affected because of its limited translocation (Mercado, 1979;

Webster, Grey, Davis, & Culpepper, 2008; Wood & Gosnell, 1966; Zandstra, Teo, & Nishimoto, 1974). Iqbal et al. (2012) assessed the effectiveness of paraquat in controlling purple nutsedge compared to glyphosate and reported that the herbicide completely kills the above ground growth of the weed but only reduced the tuber's viability by 32% compared to the control check. Standifer (1974) also compared paraquat with two other herbicides in the control of the purple nutsedge and observed that regrowth of the plants treated with paraquat was primarily from the original shoot.

The use of paraquat is however discouraged because of its acute oral toxicity and ill-health associated with operators. Paraquat is highly toxic to animals (LD_{50} for humans of 35 mg/kg and 25-50mg/kg for dogs) and has serious and irreversible delayed effects if ingested which puts it into Class II as 'moderately hazardous' by WHO classification. It is also known to have high dermal toxicity (Extenstion Toxicology Network, 1993).

Imidazolinone herbicides

Jordan (1996) compared chlorimuron (2-[[[[(4-chloro-6-methoxy-2-pyrimidinyl)amino]carbonyl]amino]sulfonyl] benzoic acid) with imazethapyr (2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-lH-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid) applied with non-ionic surfactant, crop oil concentrate, or organosilicone-based adjuvant for field control of purple nutsedge. He concluded that chlorimuron better controlled the purple nutsedge than the imazethapyr and performed better when applied with crop oil concentrate than with non-ionic surfactant or organosilicone-based adjuvant. Imazethapyr control with the organosilicone-based adjuvant or crop oil concentrate was similar and greater than imazethapyr with nonionic surfactant.

Control was greater when herbicides were applied to 2 to 6cm tall purple nutsedge compared with plants 8 to 10 cm tall in two of three trials.

Glyphosate

Glyphosate (N-(phosphonomethyl)glycine) is a non-selective systemic herbicide, especially for annual broadleaf weeds and grasses in various crops (Henderson, Gervais, Luukinen, Buhl, & Stone, 2010). Its herbicidal mode of action is to inhibit a plant enzyme involved in the synthesis of three aromatic amino acids: tyrosine, tryptophan, and phenylalanine (Sprague, 2013). It is absorbed through foliage, and minimally through roots, and transported to growing points (Henderson et al., 2010).

Glyphosate is the most widely used herbicide for the control of purple nutsedge although, under certain conditions, glyphosate application in cotton may lead to fruit shedding and yield reduction (Iqbal, Cheema, & An, 2007; Viator, Jost, Senseman, & Cothren, 2004). Glyphosate is economical, poses no herbicide carryover issues to vegetables, and minimises nutsedge tuber production; therefore, it is a suitable candidate to manage nutsedges according to Webster et al. (2008).

In a three-year study conducted in at the University of Florida to determine the effect of glyphosate on purple nutsedge, greater than 90% control of foliage was achieved with a single post-emergence application of 0.9kg ai/ha glyphosate in soybean(Edenfield, Brecke, Colvin, Dusky, & Shilling, 2005). Similar results was realized with a sequential glyphosate application of 1.1kg/ha followed by 0.6kg/ha in cotton. These treatments reduced the tuber density to less than 0.2% of non-treated plots by the third year of the study (Edenfield et al., 2005). Viability of the tubers was also reduced by 80% and 65% in soybean and cotton respectively (Edenfield et al., 2005). Webster et al. (2008) also found from their experiment to evaluate the response of purple nutsedge to glyphosate that between 0.55kg/ha and 0.58kg/ha of glyphosate was needed to reduce growth of purple nutsedge tuber biomass by 50% (I_{50}) and this rate was similar for the foliar growth. They further indicated that first-order and fourth order tubers of the weed had I_{50} values of 0.70kg/ha and 0.74kg/ha respectively. Doll (1994) emphasized the fact that since glyphosate is a non-selective herbicide, it must be applied before the crop emerges or carefully between the rows of established perennial crops, adding that it can be applied three to four weeks after seedbed preparation and then planting done without soil disturbance. The efficacy of glyphosate in the control of purple nutsedge is increased by various additives.

Herbicide combinations for control of purple nutsedge

Since herbicides have different sites of action and may either be applied pre-emergent or post-emergent, they are sometimes combined to act on different sites and/or cater for both emerged weeds and the yet-to-emerge ones. Combinations of herbicides may either result in antagonistic, additive or synergistic effect on the target weeds (Colby, 1967). Various combinations have been investigated. Brecke et al. (2005) indicated that sequential application of halosulfuron, MSMA and sulfentrazone provided at least 80% control of purple nutsedge shoots, whereas imazaquin only controlled purple nutsedge shoots by less than 65%, adding that S-metolachlor applied as pre-emergent and sequential application of MSMA and sulfentrazone may be viable treatments for control of purple nutsedge shoots and tubers. Warren and Coble (1999) also reported that imazapic and an ALS inhibitor combination treatment provided excellent shoot and tuber control, reducing their population density to less than 10% of non-treated plots.

Integrated management of purple nutsedge

Controlling purple nutsedge with a single management approach may never give the desired result unless very heavy doses are used which may be detrimental to the environment and very expensive. Best results will obtained when herbicide is integrated with mechanical weeding (Doll, 1994). Doll and Piedrahita (1977) reported that five applications of 2,4-D at 30 day interval with intermittent soil disturbances reduced tuber population by 86% , whiles the same application without soil disturbances saw no change in tuber population. Three applications of glyphosate with intermittent tillage also reduced tuber population by 72%. Brecke et al. (2005) also reported that mowing at 5cm increased control of purple nutsedge by 6% compared to not mowing.

Uses of purple nutsedge

Not much is known about the beneficial importance of the purple nutsedge. As feed for animals, it is undesirable, because it quickly becomes fibrous with age, and the tubers are distasteful, but in the absence of more desirable plants, it can serve that purpose (Holm et al., 1977; Willis, 1987). The weed has been used in landscaping in China and as a soil binder in India.

Extracts from purple nutsedge tubers have been found useful for medicinal purposes by several researchers. Many of these researchers have isolated several sesquiterpenic compounds which are among a group of naturally occurring aromatic compounds known for their pharmaceutical properties (Hikino, Aota, & Takemoto, 1968; Hikino, Aota, & Takemoto, 1967; Hikino, Aota, Kuwano, & Takemoto, 1971; Hikino, Aota, Maebashi, & Takemoto, 1967; Hikino, Suzuki, & Takemoto, 1967; Kapadia, Naik, Wadia, & Dev, 1967). M. B. Gupta, Palit, Singh, and Bhargava (1971) identified a tri- terpenoid compound that possessed antipyretic (fever reducing), anti-inflammatory, and analgesic (pain reducing) effects. Singh, Kulshrestha, Gupta, and Bhargava (1970) also found an alcoholic tuber extract to contain tranquilizing, antihistaminic, antiemetic (nausea reducing), and muscle relaxing activities along with its antipyretic and anti-inflammatory activities.

Ecological modelling as a research tool in weed management

An ecological model refers to an abstract, usually mathematical representation of an ecological system which is studied to gain understanding of the real system (Hall & Day, 1990). Ecological models are of various kinds depending on the scope of study, modelling approach, technical details and level of sophistication (Bolker, 2007).

In terms of scope and approach, models may be subdivided into two categories: one that aims for general insight into workings of ecological processes (theoretical/strategic) and one that aims to describe and predict how a particular system functions, often with the goal of forecasting or managing its behaviour. Other dichotomies are outlined by Bolker (2007). In terms of technical details, models may be analytical or computational, may represent discrete time or continuous time or may be deterministic or stochastic. Sophistication describes how complex the model is. This may be quantified by the length of the description of the analysis, or the number of lines of computer script or code required to implement the model.

Procedure for ecological modelling

The development of a model is not a one-way process but an iterative process of revisiting the previous stages when flaws are identified and new insights are gained (Balci, 1994; Jackson, Trebitz, & Cottingham, 2000). However, Bolker (2007) provided a simple road map of the modelling process as follows:

- Identify the ecological question
- Choose appropriate deterministic and/or stochastic models
- Fit parameters
- Estimate confidence intervals/test hypothesis/select models
- Put results together to answer questions or return to the first step if the question is not answered.

Modelling weed population dynamics

The dynamics of a weed population in an agro-ecosystem is governed by its intrinsic processes such as life cycle and intraspecific competition, and extrinsic processes such as the weather, management factors and interactions with other organisms (Cousens & Mortimer, 1995).

Changes in the population density of an organism are determined primarily by birth and death processes, and migration (immigration and emigration) (Radosevich, Holt, & Ghersa, 2007) with birth and immigration resulting in increased population over time and death and emigration resulting in decrease in population. Thus,

$$N_{t+1} = N_t + B - D + I - E \qquad 2.1$$

where N is number of individuals, B is births, D is deaths, I is immigration and E is emigration. These processes determine the trajectory that the plant population follows with time.

An intrinsic model of the population dynamics of a plant basically explains and predicts the trajectory of the population. Models based on just these processes may however be too general and unrealistic since it does not consider the various stage of growth and development which ultimately result in this general model (Radosevich et al., 2007)

Cousens and Mortimer (1995) categorised intrinsic models of plant populations into two: those which consider only the density of a population as a whole (single-stage models) and those that consider various stages of the plant (multi-stage models). The latter was further divided into two: models those that consider single cohorts and those that consider multiple cohorts. They proposed various difference and differential equations to describe the changes of the weed populations over time.

The effect of weather and other environmental factors on the weed population may simply be modelled with regression analysis, with the environmental factor(s) as the independent variable and the weed population as the dependent variable. Regression gives a mathematical representation of the relationship between the two variables. An important feature of regression is that it allows an estimate of various parameters and the reliability of those estimates indicated by their standard errors (Gillman, 2009).

The effect of herbicides on weed population dynamics is modelled by introducing a factor, *k,* into the intrinsic model to represent herbicide mortality and/or sub lethal effect of herbicides on seed production. If *k* is the proportion of plants killed by the herbicide, then (1-*k*) will survive the herbicide application. The intrinsic model can thus be modified with the surviving proportion of the population.

Several organisms interact with the weed in the agroecosystem, but the major one is the crop which also happens to be a plant and thus the interaction is one of competition. Definitions of competition among plants differ but they can typically be divided into two categories: those that focus on mechanisms and resource acquisitions (Grime, 2006; Tilman, 1982) and those that focus on the reduction of fitness brought by a shared requirement for a resource in limited supply. The former group of definitions are usually illustrated by mechanistic models whilst the latter ones are illustrated by phenomenological models. Competition in plants occurs both within individual species populations (intra-specific populations) and between the individuals of different populations (inter-specific competition). This results in varying effects on the plants. Models of weed population dynamics therefore take into consideration both intra- and inter-specific competitions. This is done by introducing the parameters α_{ii} (intra-specific competition co-efficient) and α_{ij} (inter-specific competition coefficient) into the intrinsic models of the plants. These parameters are quantified by the manipulation of plant population densities and proportions, and the use of regression analysis for estimation using either population growth rate or some measure of plant performance (Park, Benjamin, & Watkinson, 2003)

CHAPTER THREE

GENERAL MATERIALS AND METHODS

Introduction

A series of surveys and experiments were conducted as part of this study. This chapter first looked at the area within which the study was conducted, and then described the general procedures used which were common to various parts of the study. Procedures which were specific to the individual parts of the study were described in the respective sections.

Study Area

The study was generally targeted at Southern part of Ghana, which is located between latitudes 4^0 44" N and 7^0 10" N and longitudes 3^0 11" W and 1^0 11" E in the West African sub region. The area, which mainly consists of the Western, Central, Gt. Accra, Eastern, Ashanti and Volta regions, has varied climatic conditions and could be separated mainly into four agro-ecological zones. These are the Tropical Rainforest which covers some parts of the Western and Central Regions; the Semi Deciduous forest zone, which covers the other parts of the Western Region, most parts of the Ashanti and Eastern Regions and the middle portions of the Volta region; and the Coastal savannah which covers the other part of the Central Region, Gt. Accra and the lower parts of the Volta Region. The northern part of the Eastern and Ashanti regions are more of Transitional zones between the Semi-deciduous forest and the Guinea savannah zones (Figure 2). Each region is further divided into districts. The area under study is made up of a total of 135 political districts distributed as follows: Western Region, 22; Central Region, 16; Gt. Accra, 16; Volta Region, 25; Eastern Region, 26; and Ashanti, 30. Each district is known to produce some amount of vegetables, though at different scales of production, with the majority produced in the Transitional zone and minimal produced from the Tropical Rainforest areas.

The soils of the study area, most of which have lost their fertility due to human activities (Ministry of Food and Agriculture, 2013), were developed on thoroughly weathered parent materials, with alluvial soils (Fluvisols) and eroded shallow soils (Leptosols) common to all the ecological zones. The soils in the forest zone are grouped under Forest Oxysols and Forest Acid Gleysols. They are generally porous, well drained and loamy and are distinguished from those of the savannah zones by the greater amounts of organic matter in the surface as a result of higher accumulation of biomass. They occur in areas underlain by various igneous, metamorphic and sedimentary rocks, which have influenced the nature and properties of the soil (Ministry of Food and Agriculture, 2013). Soils of the savannah zone, are low in organic matter, have high levels of iron concretions and are susceptible to severe erosion. Thus well-drained upland areas tend to be droughty and when exposed to severe incident sun scorch, tend to develop cement-like plinthite. These conditions necessitate the heavy use of manures which have to be incorporated regularly into the soils in the savannah zone (Ministry of Food and Agriculture, 2013)

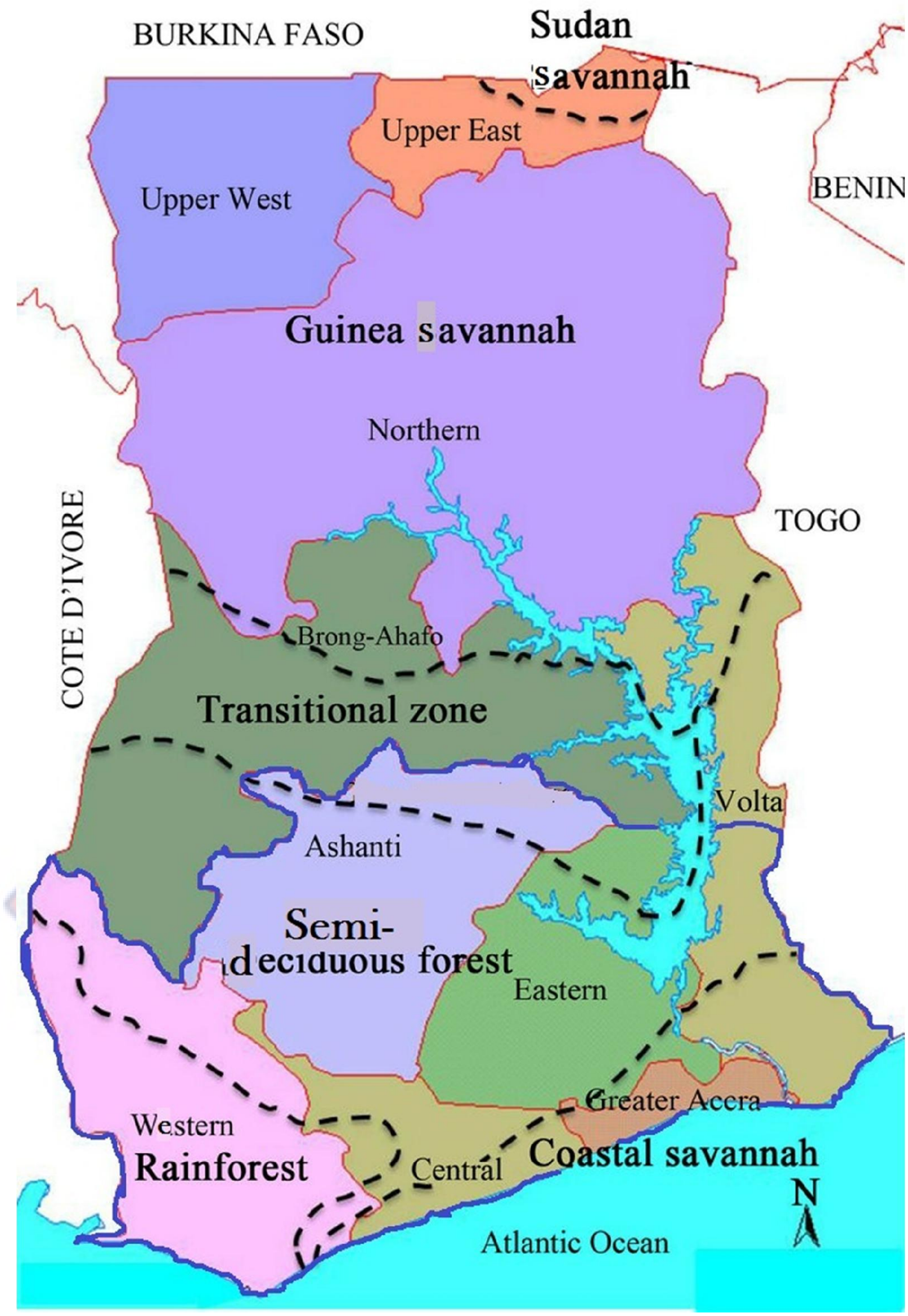


Figure 2: Map of Ghana showing the regions and agro-ecological zones in the study area (marked by the blue boundary)

The climate of the study area is influenced by the North East Trade Winds: the hot, dry and dusty-laden air mass that moves from the north east across the Sahara, and the South West Monsoon: the tropical maritime air mass that moves from the south-west across the southern Atlantic ocean. The mean monthly temperature over the area ranges from 25^{0}C to 28^{0}C with mean annual temperature averaging 27^{0}C.

The climate mainly comprises the equatorial type of bimodal rainfall pattern. Rainfall varies in amount and distribution over the agroecological zones, with the highest rainfall recorded in the rainforest and the least in the Coastal savannah. Table 1 summarizes the amount and distribution of rainfall in the four agro-ecological zones.

Table 1: Amount and Distribution of Rainfall in the Study area

Agro-ecological zone	Mean Annual rainfall (mm)	Growing period (days)	
		Major	Minor
Rainforest	2200	150-160	100
Semi Deciduous forest	1500	150-160	90
Transitional	1300	200-220	60
Coastal savannah	800	100-110	50

Source: Meteorological Services Department, Accra, Ghana

The climate of the agroecological zones is influenced by the natural vegetation of the area. The heavy rainfall of the rainforest results in dense evergreen forest with three distinct layers: the lowest layer forms a canopy at about 15m; the middle layer, about 30m whiles the upper layer consists of scattered trees which reach heights of about 45m. Lower rainfall (than the Tropical Rainforest) of the Semi-deciduous forest zone gives its characteristic feature of deciduous upper layer trees (as compared to the evergreen upper layer trees of the rainforest), with the middle and lower layers remaining evergreen. The savannah is mainly made up of dense shrubs and grasslands with the Transitional zone depicting a transition between forest and savannah vegetations.

Experimental Sites

Controlled experiments were conducted at three locations: the Technology Village of the University of Cape Coast (UCC) (where all pot experiments were carried out), the Teaching and Research Farm of UCC, and the Demonstration field of the Department of Horticulture of KNUST (field experiments were carried out at latter two sites).

Both the Technology Village and the Teaching and Research Farm of the School of the Agriculture of UCC are located in Coastal savannah agroecological zone, whereas the demonstration farm of KNUST is located in the Semi-deciduous forest zone. Prevailing climatic conditions are thus the same as described for that zone earlier.

It is reported that the soil at the Teaching of Research Farm of UCC belongs to the Benya soil series, a member of the Edina-Benya-Udu compound association. These soils are neutral to slightly acidic with pH of 6.5. They have a low nutrient status; phosphorus is about 100 ppm; Nitrogen 0.1%; low organic matter of 2% and low moisture retention capacity. They appear grayish when dry and deep brown when wet. The slope length is about 1% and soil is developed from a clay loam parent material (Asamoah, 1973).

Soil media for pot experiments

Soil medium used for pot experiments was obtained from Basakrom, a suburb of Cape Coast, located about 5km away from the Technology Village of UCC. The soil was free of the weed under study, sandy loam in texture and rich in organic matter. The absence of the weed was confirmed before each experiment by allowing the germination of the weed seed bank and ridding off every weed before setting up the experiment. The soil, together with samples from the experimental fields were first analysed for it physical and chemical properties before use and this is presented in Table 2.

Table 2: Baseline soil properties of experimental sites and potted soil media

Soil Property	Teaching and Research Farm (UCC)	Demonstration Field (KNUST)	Potted Soil media
%Nitrogen	0.09	0.19	0.10
Phosphorus (μgP/g)	5.86	19.91	23.17
Potassium (cmol/kg)	0.31	0.48	0.34
% Organic carbon	0.90	1.69	1.57
pH	6.2	6.5	6.3
Bulk density (g/cm^3)	1.29	1.30	1.35
Textural class	Sandy loam	Sandy loam	Sandy loam

Land preparation for field experiments

Prior to each field experiment, the land was first ploughed (where necessary) across the slope with the aid of a tractor mounted disc plough and later harrowed to ensure evenness. The field was then laid out and demarcated into plots as required for each field experiment with the aid of ranging poles, line and pegs, and tape measure.

Determination of soil physical and chemical properties

Soils used for the various pot and field experiments and those of the vegetable fields surveyed were analysed for both physical and chemical properties. The procedures used are here outlined.

Determination of physical properties of soils

Physical properties of soils determined included bulk density, texture, moisture contents

Bulk density and moisture content

Bulk density was determined by the procedure suggested by Rowell (1994). The soil samples were first weighed and dried at 105^{0}C until constant weight was attained, and then re-weighed to give the oven-dry weight of the soil. The bulk density was found by dividing the oven-dry weight of the soil by the volume of the core samplers used for sampling,

$$P_b\ (g/cm^3) = \frac{Mass\ of\ dry\ soil\ sample\ (Ms)}{Volume\ of\ soil\ (Vt)}$$

Where $Vt = \pi.r^2 l$

This was done for all samples collected and the mean bulk density determined.

% Soil Moisture Content (MC) was calculated as

$$MC = \frac{Mass\ of\ fresh\ soil\ sample - Mass\ of\ dry\ soil\ sample}{Mass\ Of\ fresh\ soil\ sample} \times 100\%$$

Determination of Particle Size

Soil particle size analysis was carried out using the pipette method as described by Rowell (1994). An amount of soil (10g + 0.01) was weighed into a 500 ml beaker and 20 ml of hydrogen peroxide was added and allowed to stand until frothing ceased. The suspension was then heated to complete the destruction of organic matter, and then allowed to cool. The peroxide-treated soil was transferred into a 500 ml plastic bottle and 10 ml of dispersing agent added and the soil suspension made up to 200 ml and shaken overnight. The contents were then transferred quantitatively into a 500 ml measuring cylinder and made up to 500 ml with distilled water.

The suspension was then stirred using a plunger for thorough mixing. The suspension was allowed to settle for 40s after which 25 ml of the suspension was drawn off from 10 cm below the surface into a weighed beaker. This gave the mass of silt and clay. The suspension was allowed to settle and 25 ml of the suspensions were drawn off at 10 cm depth after 5hrs. This gave the mass of clay. The pipetted suspensions were dried at 105°C till constant weight. Most of the supernatant liquid was gently decanted and the sediment was quantitatively transferred into a beaker. The sediment was repeatedly washed through stirring, settling and decanting till a clear supernatant was obtained. The sand was transferred to a weighed beaker and dried at 105°C till constant weight.

Calculations:

$$\textit{Percentage sand (m/m)} = \frac{\textit{mass of sand}}{\textit{mass of oven dry soil}} \times 100$$

$$\textit{The total mass of silt in the soil sample} = \textit{Mass in 25 ml} \times \frac{500}{25}$$

$$\textit{Percentage silt} = \frac{\textit{total silt}}{\textit{Mass of oven dry soil}} \times 100$$

$$\text{The total mass of clay in the soil sample} = \text{mass in 25 ml} \times \frac{500}{25}$$

$$\text{Percentage clay} = \frac{\text{total clay} \times 100}{\text{mass of oven dry soil}}$$

The textural classes of the soil samples were determined using the USDA textural triangle (Rowell, 1994).

Soil pH

The pH was determined by weighing 10 g of soil into a tube with a screw cap and 25 ml of distilled water was added. The sample was shaken on a mechanical shaker for 15 minutes after which the pH was determined using a pH meter (Rowell, 1994).

Determination of Total Nitrogen

A weight of between 0.5 and 1.0 g of soil sample was weighed into a digestion flask and 0.2 g of catalyst and 3 ml of concentrated H_2SO_4 were added. The contents were digested on a bloc digester at 380 °C for 2 hours. After the digestion, the digest was allowed to cool and then diluted to 50 ml with distilled water. Then an aliquot of 20 ml was pipetted into the reaction chamber of a steam distillation apparatus and 10 ml of alkali mixture was added and distillation commenced. About 40 ml of distillate was collected in a boric acid indicator. The distillate was titrated against 1/140 HCl from green to a wine colour. Blank determination was carried out alongside.

$$\% N = \frac{(S - B) \times \text{solution volume}}{10^2 \times \text{aliquot} \times \text{sample weight}}$$

Where :

S = Sample titre

B= blank titre

Determination of Available Phosphorous

One gram (1g) of soil sample was weighed into a 15 ml centrifuge tube and 10 ml of Bray No. 1 extracting solution was added. The suspension was agitated for 15 minutes on a mechanical shaker. The suspension was filtered and 2 ml aliquot of the filtrate was pipetted for colour development using ascorbic acid.

Determination of Potassuim

Potassium(K) in the digested samples were determined using a flame photometer. In the determination, the following working standards of K were prepared: 0, 2, 4, 6 8 and 10µg/ml. The working standards as well as the sample solutions were aspirated individually into the flame photometer and their emissions (readings) recorded. A calibration curve was plotted using the concentrations and emissions of the working standards.

The concentrations of the sample solutions were extrapolated from the standard curve using their emissions

Calculation.

$$\mu gK/g = \frac{C\ X\ solution\ volume}{Sample\ weight}$$

(Stewart, Grimshaw, Parkinson, & Quarmby, 1974)

Determination of Organic Carbon

Between 0.5 – 1 g of soil sample was weighed into a 500 ml conical flask and 10 ml of 0.1667M K_2Cr_2O solution and 20 ml concentrated H_2SO_4 were added. The contents were thoroughly mixed and the reaction allowed for 30 minutes to complete. The reaction mixture was diluted with 200 ml of distilled water and 10 ml of H_3PO_4, 10 ml of NaF solution and 1ml of diphenylamine indicator were added and titrated against 0.5 M ammonium ferrous sulphate solution to a green colour. A blank was ran alongside the samples.

Calculation:

$$\%\ organ\ carbon = \frac{(B - S)\ X\ molarity\ of\ Fe^{2+}\ X\ 0.003\ X\ 100}{Weight\ of\ sample\ X\ \ 77}$$

Where

B = Blank titre

S = sample titre

(Motsara & Roy, 2008).

Procedures for determining plant population, growth and yield

Purple nutsedge shoot and tuber counts were necessary throughout the study for field surveys, field and pot experiments. The growth and yield of other crops (especially cabbage) was also necessary for a number of experiments. These procedures used in determining these parameters are presented here.

Weed shoot count

Purple nutsedge shoots were counted with respect to area, with the aid of quadrats (quadrat size depended on the specific study). The total number of emerged shoots which either completely or at least half-way fell in the quadrat, were counted and expressed as per area of quadrat. The counts were then converted to per metre square by dividing by the area of the quadrat (in m^2). For pot experiments, the total number of shoots counted was divided by the cross-sectional area of the pot in converting them to per m^2.

Estimation of number of tubers

The number of purple nutsedge tubers in the soil was estimated per unit area to a depth of 10cm for field works or respective depth for pot experiments. This was in view of the fact that most vegetables extend their roots within the top 10cm of the soil.

The tuber population was estimated with the aid of a hoe with blade length 10cm and width 7cm. The hoe was used to dig out the soil at sampling various points on the field. The volume of soil was measured with one-litter plastic beaker and the number of purple nutsedge tubers present counted. The number of tubers counted was converted to per m^2 by dividing it by the area of the hoe blade (0.007m^2). For pot experiments, the soil was carefully spread over a plastic sheet the tubers picked out and counted. In instances where distinguishing tubers from soil lumps became difficult, the soil was first put in

2mm sieve and carefully washed out under running water. This left the larger soil particles and the tubers on the sieve making counting easier.

Plant height

Plant height was taken as the length from ground level to the highest point of the plant in its natural orientation. It was taken in either centimetres or metres with the aid of meter rule.

Number of unfurled leaves

Number of leaves which had not folded were counted by direct observation and recorded as the number of unfurled leaves per cabbage.

Length and Width of largest leaf

The largest leaf of the cabbage plant was determined by direct observation and chosen for the determination of these two parameters. Leaf length was measured from lamina tip to the point of attachment of the petiole to the stem, along the midrib of the lamina, while leaf width was measured from end-to-end between the widest lobes of the lamina perpendicular to the lamina mid-rib.

Leaf Area and Leaf Area Index

Leaf area (LA) was calculated from the leaf width with the linear regression equation suggested by Olfati, Peyvast, Shabani, and Nosrati-Rad (2010) as

$$LA = 21.72 + 0.0073\ W^2$$

Leaf area index (LAI) was then determined by dividing the leaf area by the ground area.

$$LAI = \frac{Leaf\ area}{Ground\ area}$$

Total plant fresh weight

The whole plant was uprooted with the aid of an earth chisel, where necessary, and soil particles washed off. The plant was then weighed with a top-pan balance

Data processing and presentation

Data collected was collated and organized using Microsoft Excel 2010 and analysed with appropriate statistical procedures using Genstat Discovery Edition 4 (VSN International, 2011), R studio Version 0.99.892 (R Core Team, 2015). The appropriate statistical procedures for the individual sections have been described in the respective sections.

CHAPTER FOUR

AGRONOMIC PRACTICES, FARMERS' PERCEPTION AND THE PREVALENCE AND MANAGEMENT OF *Cyperus rotundus* L. IN VEGETABLE FIELDS OF SOUTHERN GHANA

Introduction

Vegetables comprise a very important part of Ghanaian diets and hence are produced in almost every part of the country. They may be exotic, for example, lettuce, cabbage, cauliflower, onion, spinach, carrot, French beans, etc. or local, such as tomato, hot pepper, okra, garden eggs, shallot, etc. They are generally, short-lived (between 3 weeks to 6 months, even though some can live for longer periods), succulent and susceptible to adverse weather conditions, pests and diseases. Hence they demand much care on the field of production. Various agronomic practices are thus employed to ensure good yields. These practices include methods of land preparation, sowing, irrigation, insect pest and disease management, weed control and harvesting. They are important and worth considering in the modeling of the population dynamics of the widespread weed, *Cyperus rotundus* L. in those fields since they may have direct (or indirect) impact on it.

Cyperus rotundus is reportedly found in more countries, regions and localities than any other weed (Holm *et al.*, 1977). It is generally known to be common in southern Ghana, especially in vegetable fields, but the current prevalence rate and methods of managing it are not well documented. Documenting these will help in the study of its ecology which will in turn help in designing appropriate management methods for it.

Thus, the first objective of this section was to document various agronomic practices employed in vegetable fields in southern Ghana, especially in the *C. rotundus* infested fields, to aid in the system analysis for the design of the model of the population dynamics of the weed in those fields. The second objective was to document the prevalence rate, farmers' perception and common methods of managing the *C. rotundus* in the study area.

Materials and Methods

The study was conducted in the form of interviews with vegetable farmers, and field assessments in the study area (southern Ghana).

Study area

The study was carried out in the southern part of Ghana described under study area in Chapter three of this work (pages 46 to 50)

Sampling procedure

To ensure good representation of the various scales of production, the important vegetable growing districts as recommended by the Regional Management Information System (MIS) officers of the Ministry of Food and Agriculture, were stratified into three, according to farm size and estimated population of vegetable farmers after an initial reconnaissance survey as follows:

- **Large scale** production (over 2000 farmers, with average farm size above 1.2 hectares per farmer),
- **Medium scale** (between 500 and 2000 farmers, with farm size between 0.4 and 1.2 hectares per farmer) and
- **Small scale**, (less than 500 farmers, with average farm size below 0.4 hectare).

Following the stratification, three districts were selected from the large scale, five from the medium scale and four from the small scale in accordance with the number of districts in each category, to give a total of 12 districts for the survey. The selection was also done to ensure fair representation of the six regions and the four agro ecological zones. The selected districts are listed in Table 3.

The corresponding numbers of vegetable farmers (Table 4) were chosen at random from each of these districts for interview. The interviews were conducted in the respective local languages.

Table 3: List of selected Districts for surveys

District	Region	Scale of production	Agro-ecological zone	No of farms sampled
Sekondi – Takoradi	Western	Small	Coastal savannah	13
Wassa East	Western	Small	Tropical Rainforest	13
Ekumfi	Central	Small	Coastal savannah	16
K. E. E. A	Central	Medium	Coastal savannah	15
Accra Metropolis	Gt. Accra	Medium	Coastal savannah	12
Dangme West	Gt. Accra	Small	Coastal savannah	8
Bekwai	Ashanti	Medium	Semi deciduous	17
Ejura	Ashanti	Large	Transitional zone	10
Fanteakwa	Eastern	Large	Transitional zone	19
Suhum/Kraboa/ Coaltar	Eastern	Large	Semi deciduous	16
Keta	Volta	Medium	Coastal savannah	15
Total				154

A total of 154 vegetable farmers, consisting of 135 males and 19 females, aged between 22 years and 75 years were interviewed on various agronomic practices including land preparation, planting, irrigation, pest and disease control and soil management (see Appendix I for questionnaire). Their perception about the purple nutsedge was also sought. The respondents were shown samples and/or pictures of the weed (Appendix II) for identification before their views on the weed were sought. The interviews were carried out between July 2014 and February 2015

Field assessment for purple nutsedge infestation

Sampling quadrats of size 50cm × 50cm were used to sample 20 points per acre (approximately 0.4ha) at random in each vegetable field. Each quadrat was assessed for the presence or absence of the purple nutsedge and, if present counted to estimate the frequency of occurrence and the population density of the purple nutsedge shoots. Tuber density was also estimated as described earlier.

Soil sampling

Two sets of soil samples were taken for analysis from each field: the first for bulk density and soil moisture content and the second for the determination of other soil physical and chemical properties.

For bulk density, between three and five samples were taken per acre (approximately 0.4 ha) of field with sampling cylinders of diameter 3cm. The sampling cylinder was placed vertically against the soil and gently hammered with a driving tool into the soil until the soil projected a few millimeters above of the cylinder. The cylinder plus soil was excavated leaving extra soil extending from each end of the cylinder. The ends of the cylinder were trimmed and the soil samples emptied into transparent polyethene bags, sealed tightly and sent to the laboratory for analyses.

In the case of soil sampling for determination of other parameters, five soil samples were randomly taken with the aid of an auger from a depth of approximately 15cm. The soil samples were bulked together and a composite sample was taken, packaged in transparent polyethene bags and labelled accordingly for the determination of soil total nitrogen, available phosphorus, exchangeable potassium, organic matter contents and pH.

Global Positioning System (GPS) Readings and Climatic Data

The locations of the various farms were determined with a GPS device (Gamin Etrex 20) for the purposes of field identification and the assessment of the impact of environmental factors on the distribution of the weed. Climatic data of the surveyed areas for the years 2014 and 2015 were obtained from the Meteorological Services Department. The field assessments were carried out concurrently with the interviews between July, 2014 and February, 2015.

Data Analysis

The data collected were summarized using simple frequencies, means with standard errors and/or analysed, with regression and appropriate non-parametric procedures where necessary, using the Statistical Package for Social Scientists (SPSS version 17).

Results and Discussion

General observation

Vegetable production was observed to be practiced in all districts visited, including both selected and non-selected districts for the final survey. Farmers in the Coastal savannah areas, such as Accra, Keta and Takoradi were mainly into the production of only vegetables all year round, while those in the Semi-deciduous forest zone combined vegetable production with either plantation crops such as cocoa, or some arable crops usually on different pieces of land. For fields which were close to streams and/or other water bodies, vegetable production continued even through the dry season, however, production was always stalled in the dry periods of the year for fields not close to such sources of water. In some other places such Ejura, farmers had a regular cycle for crop production, with serious vegetable production taking place only in the minor rainy season.

Exotic vegetables such as cabbage, lettuce, carrot and sweet pepper were mainly cultivated in the urban and peri-urban areas such as Accra, Takoradi, Kumasi and Mampong (the latter two were not selected for the final survey) whiles local vegetables such as okro, pepper, tomatoes and garden eggs constituted the major vegetables cultivated in the rural areas.

Agronomic practices in vegetable fields

Land Fallowing and Preparation

Land fallowing is important to replenish the land after a period of usage. The survey showed that 37.3% of valid respondents did not practice land fallowing. The remaining practiced at least, some level of fallowing for periods between 6 months and 4 years with the modal (42.4%) fallowing period between 1 and 2 years. The result is presented in Table 4.

Table 4: Length of Fallow before cropping

Fallow Period	Frequency	Valid Percent	Cumulative Percent
No Fallow	44	37.3	37.3
6 months	10	8.5	45.8
1-2years	50	42.4	88.1
3-4years	13	11.0	99.2
Not sure	1	0.8	100.0
Total	118	100.0	

The larger percentage of the respondents practicing land fallowing is an indication of the farmers' understanding and acceptance of the concept of land fallowing. This confirms the statement by Styger and Fernandes (2006) that fallowing, though as old as agriculture itself, still forms an integral part of many tropical farming systems. It is vital in ensuring that the soil regains its fertility after a period of usage. The results however indicate that the majority (88.1%) practice land fallowing only up to two years. This is in line with the findings by Osabuomen and Okoedo-Okojie (2011) and Kumar (1993) that long periods of land fallow is no longer a common practice in West Africa because of population pressure and land availability. Shortening fallow period however, eliminates many stages of natural vegetation succession (Food and Agriculture Organization, 2006) which would normally have resulted in nutrient replenishment and the breaking of pest and disease cycles. The scarcity of arable land in a number of vegetables growing areas may, as well be the reason for the 37.3% which did not practice land fallowing.

Burning before planting

The results in Table 5 showed that burning before planting was practiced by 73 out of 144 valid respondents, representing a little more than half of valid respondents (50.7%). Asked how many times the land had been burnt over the past three years, 59 of them indicated they had burnt it once or twice whiles 24 of them said they had burnt it between 3 and 4 times. Of the 71 who answered in the negative to the previous question on burning, 11 conceded that their fields had been burnt once or twice within the past three years. The results are presented in Tables 5, 6 and 7.

Table 5: Burning before planting

Response	Frequency	Valid Percent	Cumulative Percent
yes	73	50.7	50.7
no	71	49.3	100.0
Total	144	100.0	

Table 6: Number of times of burning over past 3 years

	Frequency	Valid Percent	Cumulative Percent
once or twice	59	59.0	59.0
between 3 and 5 times	24	24.0	83.0
none	17	17.0	100.0
Total	100	100.0	

Table 7: Cross-tabulation between burning before planting and number of times of burning over previous 3 years

		No. of times of burning over past 3 years				
		once or twice	between 3 and 5 times	more than five times	none	Total
Burning before planting	yes	48	24	0	0	**72**
	no	11	0	0	16	**27**
Total		59	24	0	16	99

The practice of bush burning for cultivation has been described as inimical to soil fertility and biodiversity. Burning destroys the litter layer and so diminishes the amount of organic matter returned to the soil. The organisms that inhabit the surface soil and litter layer are also eliminated (Bot & Benites, 2005). However some farmers deem it cheap and easier to clear their fields. The result indicates that the practice is common among some vegetable farmers and this must be discouraged for sustainability of the country's agriculture.

Method of Land Preparation

The result showed that 50 out of 140 valid respondents, representing 36% prepared their fields by slashing and burning whereas 46, representing 33% employed slashing and hoeing for land preparation (Figure 3). Use of tractor was minimal among the farmers interviewed (9%). Others also resorted to use of herbicides (15%) and other forms of integrated management (7%).

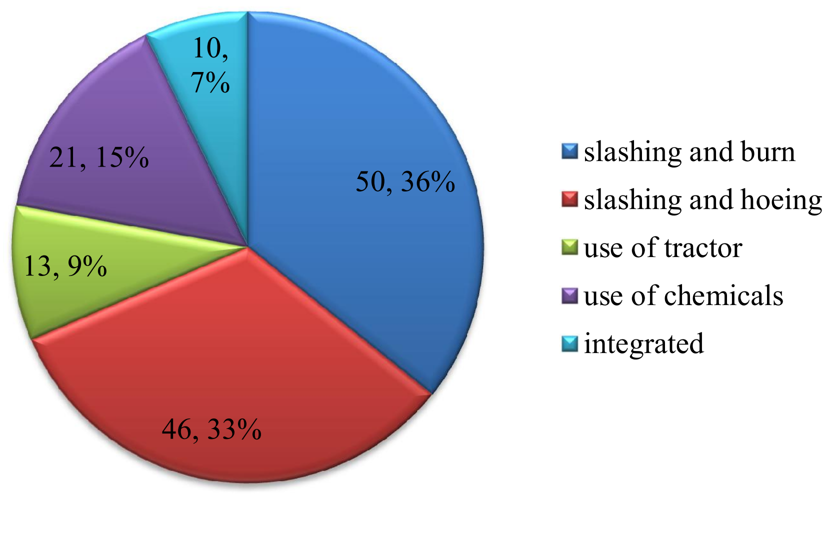


Figure 3: Methods of land preparation used by respondent

Majority of the vegetable farmers still employ the traditional system of land preparation where the farmers use simple tools such as cutlass and hoes which is known to be labour intensive, and time consuming. This is in line with the report of the Ministry of Food and Agriculture (2013). Use of tractor, which could have been much easier and faster, is still low probably due to its expensive nature. Again, the concept of integrating various methods does not seem to have been well accepted by these farmers. For improved production, farmers will have to be encouraged to change from the traditional methods of land preparation.

Use of Fertilizers

Majority of the respondent (90.3%) answered in the affirmative when asked if they used fertilizers (Table 8), with most of them saying they were using N.P.K. (55.4%). Use of manures was observed to be on the low side (15.3%) (Figure 4)

Table 8: Fertilizer Use by respondents

	Frequency	Valid Percent	Cumulative Percent
yes	121	90.3	90.3
no	13	9.7	100.0
Total	134	100.0	

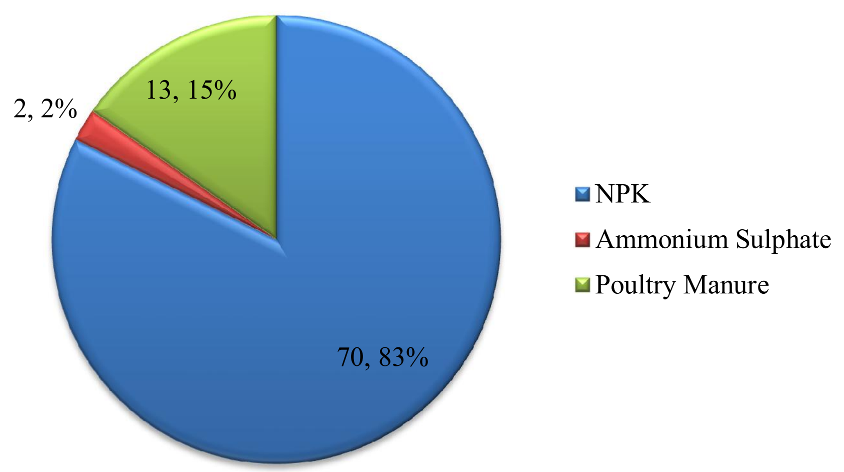


Figure 4: Kinds of fertilizers used by respondents

Fertilizers are used to improve soil fertility and ensure proper growth and yield of crops. Its high use among the farmers perhaps suggests that most vegetable fields have inadequate soil nutrients and this is confirmed by the Ministry of Food and Agriculture (2013). This is also expected, given the low periods of fallow by the farmers (Table 4) which is expected to result in depletion of soil nutrients. Again most farmers prefer to use NPK fertilizers which are soon used up by plants or even leached and hence have to be used consistently. Manures which could have ensured longer periods of soil fertility are rather not popular among the farmers. This may be due to the unavailability of the manures or the difficulty in transporting them as asserted by some of the farmers (B. Sagodo, personal communication, November 6, 2015)

Irrigation

On irrigation, a total of 89 out of 134 valid respondents representing 66.4% indicated they practice some form of irrigation, either with water from a nearby river or a dugout well. The remaining practice rain-fed agriculture. (Table 9)

Table 9: Source of Irrigation water

	Frequency	Valid Percent	Cumulative Percent
Rain water	45	33.6	33.6
Nearby stream	68	50.7	84.3
Dug out well	21	15.7	100.0
Total	134	100.0	

Ghana's agriculture is known to be primarily rain-fed with few irrigated farms (Kyei-Baffour & Ofori, 2006). The story is however slightly different with vegetable production which seems to rely much more on irrigation. This is probably due to the fact that vegetables generally require much water and hence farmers are compelled to find various means of irrigation in the absence of rainfall. The results agree with the findings by Asare-Bediako and Micah (2014) which put irrigation with watering cans/buckets (from nearby streams and dug out wells) ahead of rain-fed vegetable production in the Western and Ashanti Regions of Ghana.

Insect Pest and Disease Management

Asked how they managed pests and diseases on their fields, only 7 out of the 126 valid respondents (5.6%) said they rely solely on cultural control methods (organic), with 19.0% augmenting the cultural methods with minimal use of pesticides (Integrated Pest Management). The majority (75.4%) however, used predominantly pesticide for the control of pest and disease. (Table 10)

Table 10: Methods of insect pests and disease control by respondents

	Frequency	Valid Percent	Cumulative Percent
Cultural Control only	7	5.6	5.6
Predominantly Cultural	24	19.0	24.6
Predominantly Pesticides	95	75.4	100.0
Total	126	100.0	

Insect pests and diseases constitute a major setback in vegetable production in the study. The high rate of pesticide use in the control of these pests and diseases confirms the assertion by Afari-Sefa, Asare-Bediako, Kenyon, and Micah (2015) that use of pesticides among farmers is fast increasing. These pesticides are seemingly more effective, less laborious and often cheaper, than the cultural methods and hence the wide use. They however can have detrimental effects on the environment and the agro-ecosystem as a whole.

Weed Management

Specifically on weed management, 72 out of 118 valid respondents representing 61% used simple tillage tools such as hoes, hand fork for weed management after planting. Herbicide use was minimal (20%) (Figure 5).

First follow-up weeding for the vast majority of the respondents (88.7%) was usually carried out between the 2 to 4 weeks after planting (Table 11). The number of times of weeding ranged between 3 and 5 for most respondents (70.7%) with a few doing it once or twice, or more than 5 times (Table 12)

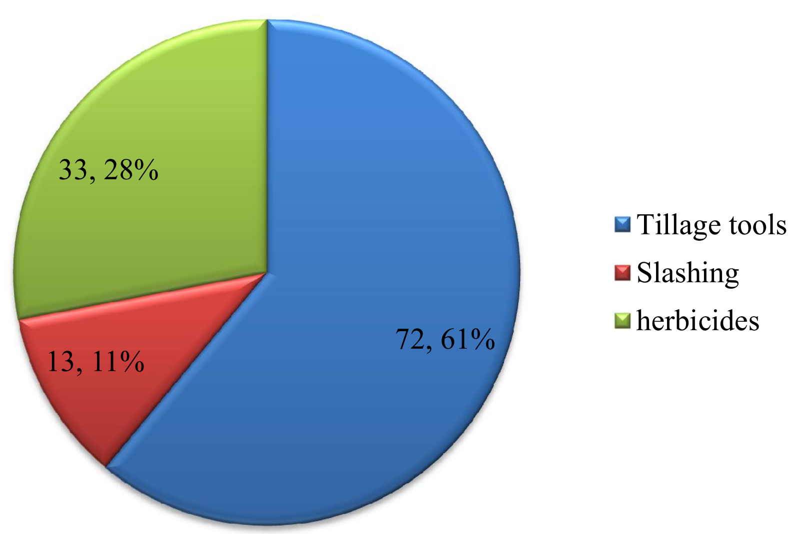


Figure 5: General Methods of Weed control by respondents

Table 11: Weeks to first follow-up weeding after planting

Weeks after planting	Frequency	Valid Percent	Cumulative Percent
1	8	7.0	7.0
2	25	21.7	55.7
3	56	48.7	77.4
4	21	18.3	95.7
>4	5	4.3	100.0
Total	115	100.0	

Table 12: No. of times of Weeding after planting

	Frequency	Valid Percentage	Cumulative Percentage
Once or twice	18	15.5	15.5
between 3 and 5 times	82	70.7	86.2
more than five times	16	13.8	100.0
Total	116	100.0	

The responses from the farmers about the methods of weed control confirms the notion that Ghana's agriculture still relies mainly on simple farm implements like hoes and cutlasses (Asare-Bediako & Micah, 2014). The minimum use of herbicides for weed control on cropped field, relative to the high use of other pesticides, is due to the unavailability of selective herbicides on the market. The period it takes to apply any weed control method, and frequency of weeding depend on the rate of growth of the weeds and the critical period of competition of the crop. Hence, the variation in the period to first follow-up weeding and the number of times a farmer weeds his field before harvest.

The weed under study, the purple nutsedge, has a rapid growth rate and therefore to minimize its impact on vegetable crops, it has to be weeded more often.

Farmers' perception of *Cyperus rotundus*

Identification, local names and uses of purple nutsedge

A total of 121 out of 154 farmers interviewed were able to identify the weed when they were shown a sample and/or picture of the weed (Table 13). This they did with further description of its biology and ecology. This confirms its widespread and popularity among the famers from different parts of the country and affirms the fact that it is a cosmopolitan weed.

Table 13: Identification of purple nutsedge

	Frequency	Valid Percent	Cumulative Percent
yes	121	78.6	78.6
no	33	21.4	100.0
Total	154	100.0	

Asked how it was called in the local dialect, most Akans (Ashanti and Eastern Regions) referred to it as "shia me ndɔn num" which literally means "meet me at five o'clock", implying that the weed regrows by 5pm if cleared in the morning. Other Akans also called it "atadwe", "nkonkona atadwe" and/or "atadwefuw" which means "tigernut", "crow's tigernut" and "tigernut weed" respectively. These names depict the weed's relation to its closest relative, the yellow nutsedge, which is commonly called tigernut in southern Ghana. In the Volta Region, the farmer folks called it "fiogbe" whereas it was called "dagase" in the Greater Accra Region. The results are presented in Table 14

Table 14: Common names of purple nutsedge in Southern Ghana

Region of survey	Common local language	Common name for purple nutsedge
Western	Akan	Atadwe/atadwefuw
Central	Akan	Nkonkona atadwe
Gt. Accra	Ga	Dagase
Volta	Ewe	fiogbe
Eastern	Akan	Atadwe/atadwefuw
Ashanti	Akan	Atadwe/atadwefuw

On the uses of the weed (Table 15), three of the farmers indicated the weed could be used to feed animals, with another three suggesting it could be used for mulching. The remaining 148 did not know of any use for the weed.

Table 15: Respondent's perception of uses of the purple nutsedge

	Frequency	Valid Percent	Cumulative Percent
Feeding of animals	3	1.9	1.9
Mulching	3	1.9	3.8
Not sure	148	96.2	100.0
Total	154	100.0	

Feeding of animals with the purple nutsedge is not a popular practice and might only be considered in the absence of preferred forage or when green matter is extremely limited (Willis, 1987). Again mulching with the weed might only be possible with dried leaves of the weed, considering the fact that the underground structures have a prolific sprouting rate when conditions are favourable. The six respondents who gave these answers therefore might not have been able to identify the weed, or were possibly making guesses on what it could be used for. The vast majority of the respondents not knowing any use for it, however, confirms the fact that not much is known about the use of the purple nutsedge.

Occurrence of purple nutsedge on vegetable fields

When asked if they had observed the weed on their vegetable fields, 104 (81.9%) responded in the affirmative with 23 (18.1%) responding in the negative (Table 16). Out the 104, 86 indicated that the weed was still on the field as at the time of interview (Table 17). Compared to other weeds, 53 of the 86 ranked the weed as the worst weed on the field with 27 ranking it as an important weed but not the worst. Six however indicated that the weed was not an important one (Table 18). Their reasons for the ranks assigned were mostly based on the difficulty in control and its effect on the crop growth and yield. Questioned about the season when the weed was much problematic, 45.5% of the farmers indicated that it was problematic throughout the year with 43.3% saying it was problematic in the wet period. About 6.5% of the farmers held the view that the weed was a problem in the dry season (Tables 19).

Table 16: Presence of purple nutsedge on vegetable fields

	Frequency	Valid Percent	Cumulative Percent
yes	104	81.9	81.9
no	23	18.1	100.0
Total	127	100.0	

Table 17: Continued existence of purple nutsedge on vegetable fields

	Frequency	Valid Percent	Cumulative Percent
yes	86	82.7	82.7
no	18	17.3	100.0
Total	104	73.4	

Table 18: Relative ranking of noxiousness of purple nutsedge

	Frequency	Valid Percent	Cumulative Percent
The worst weed	53	60.2	60.2
An important weed but not the worst	27	33.0	93.2
Not an important weed	6	6.8	100.0
Total	86	100.0	

Table 19: Problem period of weed

	Frequency	Percent	Valid Percent	Cumulative Percent
Wet season	38	24.7	43.2	43.2
Dry season	8	6.5	11.4	54.5
All year round	40	26.0	45.5	100.0
Total	86	57.1	100.0	

The widespread nature of the weed across the study area is indicated by the fact that majority of the respondents had at a point in time observed it on their fields and was well known among the farmers. However, due to persistent management of the weed (as indicated by some of the famers), the weed was no longer found on some of the fields. This suggests that some management practices (perhaps employed over time) could lead to eradication of the weed from vegetable fields despite the difficulty in control.

As expected, majority of the farmers who still had it on their fields said it was either the most noxious weed or was among the noxious weeds on the field. This is in line with declaration of the weed as the world's worst weed by Holm *et al.* (1977). The reasons given were as well similar to the reasons assigned by Holm *et al* in their declaration.

The weed, according the majority of the farmers, poses the problem in the wet season more than the dry season, which also confirms the statement by Stoller and Sweet (1987) that moisture is the major stimulant for the proliferation of the weed. For fields close to streams and other water bodies, the problem may persist throughout the year, because of the availability of moisture on the field. In the dry period however, fields with low moisture contents might not have the weed as a problem. Nevertheless, due to irrigation, most farmers have the problem throughout the year.

Perceived effect of the purple nutsedge on vegetable production

With regards to the major problem posed by the weed, views of farmers were divergent; 71 out of the 83 valid respondents, representing 85.5% stated growth and yield reduction as their major concern. Reduction in market value was cited by only three respondents with nine complaining about the increase in production cost due to management of the weed. Table 20 shows the results.

Table 20: General effect of purple nutsedge vegetable production

	Frequency	Valid Percent	Cumulative Percent
Reduces rate of growth	26	31.3	31.3
Reduces crop yield	45	54.2	85.5
Reduces market value	3	3.6	89.2
Increases cost of production	9	10.8	100.0
Total	83	100.0	

When asked to rank the percentage yield reduction on a scale of 0 (no damage) to 10 (total damage) caused by the weed, 64.0% of the respondents ranked the damage between 4 and 5 with the highest rank being 8, given by only one person. The least score of 1 was also given by one person.

Table 21: Respondents' perception of yield reduction rate

Rank	Frequency	Valid Percent	Cumulative Percent
1	1	1.6	1.6
2	2	3.3	4.9
3	6	9.8	14.8
4	27	44.3	59.0
5	13	19.7	78.7
6	5	6.6	85.2
7	4	1.6	86.9
8	1	1.6	88.5
9	0	4.9	93.4
10	0	1.6	95.1
Total	61	100.0	

Scale: 0 (no damage) to 10(total damage)

The weed is known to negatively affect both growth and yield of crops, their market value in some cases, as well as the cost of production (Doll, 1994). However farmers' major concern was on the reduction of growth and yield of their crops.

The major method of weed management in already cropped fields was by the use of simple tillage tools such as hoe and handfork for majority of the farmers who had the weed on their farm, with others slashing and /or using herbicides. These control measures used, however, were rated excellent by only seven of them with 40 rating them as adequate and 37, as inadequate (Tables 22 and 23).

A cross tabulation of the method of control against its effectiveness showed a significant dependence (p = 0.015) of effectiveness on method of control (Table 24). The highest unstandardized residuals were observed under use of tillage tools, where more respondents (8 more than expected) indicated that the method was inadequate and less (approximately 5 less than expected) indicated that it was adequate despite the high number that indicated that it was adequate.

Table 22: Respondent's methods of controlling the purple nutsedge

	Frequency	Valid Percent	Cumulative Percent
Tillage tools	52	53.5	53.5
Slashing	17	19.8	73.3
Herbicides	13	15.1	95.3
Others	4	4.7	100.0
Total	86	100.0	

Table 23: Effectiveness of control method

	Frequency	Valid Percent	Cumulative Percent
Excellent	7	8.1	8.1
Adequate	40	46.5	54.7
Inadequate	37	43.0	97.7
Very poor	2	2.3	100.0
Total	86	100.0	

Table 24: Cross tabulation of method of purple nutsedge control and effectiveness of control method

Method of purple nutsedge Control	Effectiveness of Control Method				Total
	Excellent	Adequate	Inadequate	Very poor	
tillage tools	2 (-1.8)	16 (-5.1)	28 (8.0)	0 (-1.1)	46
slashing only	3 (1.6)	8 (0.2)	4 (-3.4)	2 (1.6)	17
use of tractor	0 (-0.4)	4 (1.7)	1 (-1.2)	0 (-0.1)	5
herbicides	2 (0.9)	7 (1.0)	4 (-1.7)	0 (-0.3)	13
Others	0 (-0.3)	4 (2.2)	0 (-1.7)	0 (0.0)	4
Total	7	39	37	2	85

Pearson $\chi^2_{(df=12)} = 25.065$,

$p = 0.015$

Figures in parentheses represent unstandardized residuals

Contribution of some Agronomic Practices to the persistence of the weed on vegetable fields

About 82.7 per cent of the farmers who earlier indicated that the weed was present on their field later said it was no more present (Tables 16 and 17). Hence the persistence of the weed was tested for its dependence on some agronomic practices employed by the farmers. These included burning before planting, frequency of burning, land preparation, cropping system, fertilizer use, irrigation and method of weed control on cropped fields. No significant dependence was observed for burning before planting (Table 25), frequency of burning (Table 26), method of land preparation (Table 27), cropping system (Table 28), irrigation (Table 30) and method of weed management (Table 31). Significant dependence was however observed only for fertilizer use (Table 29), where the purple nutsedge was found to be significantly higher for fields that used fertilizers (mainly NPK).

Table 25: Burning before planting

Burning before planting	Purple nutsedge still on field		
	yes	no	Total
yes	45 (-2.0)	13 (2.0)	58
no	53 (2.0)	10 (-2.0)	63
Total	98	23	121

Pearson $\chi^2_{(df=1)} = 0.839$

$p = 0.360$

Fisher's Exact Test = 0.487

Figures in parentheses represent unstandardized residuals

Table 26: Frequency of burning

No. of times of burning over past 3 years	Purple nutsedge still on field		
	yes	no	Total
once or twice	38 (0.3)	8 (-0.3)	46
between 3 and 5 times	17 (-1.0)	5 (1.0)	22
none	13 (0.7)	2 (-0.7)	15
Total	68	15	83

Pearson $\chi^2_{(df=2)} = 0.564$
$p = 0.754$
Figures in parentheses represent unstandardized residuals

Table 27: Method of land preparation

Method of Land Preparation	Purple nutsedge still on field		
	yes	no	Total
slashing and burn	31 (-1.0)	8 (1.0)	39
slashing and hoeing	33 (1.0)	6 (-1.0)	39
use of tractor	8 (-2.7)	5 (2.7)	13
use of chemicals	14 (0.9)	2 (-0.9)	16
integrated	10 (1.8)	0 (-1.8)	10
Total	96	21	117

Pearson $\chi^2_{(df=4)} = 0.573$
$p = 0.160$
Figures in parentheses represent unstandardized residuals

Table 28: Cropping system

Cropping System	Purple nutsedge still on field		
	yes	no	Total
mono cropping	39 (0.6)	8 (-0.6)	47
mixed cropping	55 (-0.6)	13 (0.6)	68
Total	94	21	115

Pearson $\chi^2_{(df=1)} = 0.082$

$p = 0.775$

Fisher's Exact Test = 0.812

Figures in parentheses represent unstandardized residuals

Table 29: Fertilizer use

Fertilizer Use	Purple nutsedge still on field		
	yes	no	Total
yes	87 (3.9)	14 (-3.9)	101
no	6 (-3.9)	6 (3.9)	12
Total	93	20	113

Pearson $\chi^2_{(df=1)} = 9.616$

$p = 0.002$

Fisher's Exact Test = 0.007

Figures in parentheses represent unstandardized residuals

Table 30: Irrigation

Source of Irrigation water	Purple nutsedge still on Field		
	yes	no	Total
Rain water	29 (-2.1)	9 (2.1)	38
Nearby stream	48 (1.4)	9 (-1.4)	57
Dug out well	17 (0.7)	3 (-0.7)	20
Total	94	21	115

Pearson $\chi^2_{(df=2)} = 1.125$

$p = 0.570$

Figures in parentheses represent unstandardized residuals

Table 31: Method of weed management on cropped fields

Method of Weed control	Purple nutsedge still on Field		
	yes	no	Total
Tillage tools	30 (0.5)	7 (-0.5)	37
Slashing only	6 (-2.0)	4 (2.0)	10
hoeing	23 (3.1)	2 (-3.1)	25
herbicides	20 (-1.5)	7 (1.5)	27
Total	79	20	99

Pearson $\chi^2_{(df=3)} = 5.327$

$p = 0.149$

Figures in parentheses represent unstandardized residuals

The fact that the persistence of the weed did not depend on most of the agronomic practices confirms the notion that purple nutsedge does well in a wide range of conditions and cannot easily be eradicated by such agronomic practices which include burning and weed management.

Contrary to thoughts that burning before planting could destroy the purple nutsedge tubers (since the tubers can hardly withstand the high temperature from burning, as reported by Horowitz (1992)), and hence rid of the weed, a large number (45) of those who indicated that they burnt their fields before planting still complained of the presence of the weed of the fields, debunking the notion that the tubers could be destroyed completely by burning. This may have been due the fact that some of the tubers were buried at a depth away from the burning effect of the fire and hence remained viable and were able to sprout later. The same reason might apply for the non-dependence of the weed's persistence on consistent burning.

Purple nutsedge persistence also did not depend on the method of land preparation employed by the farmers, suggesting that the available methods could not effectively eliminate the weed despite the fact that land preparation could adversely affect the weed. Slashing only reduces the above ground portions of the weed, which mainly comprises leaves, without any effect on the below ground portions which are responsible for the subsequent proliferation of the weed. This is not likely to be effective in eliminating the weed from an infested field. Tillage operations employed in land preparation such as hoeing and ploughing are known to affect the weed both positively and negatively. While they bring up buried tubers to the soil surface and expose them adverse to weather conditions, they also break tuber dormancy when the tuber chains are severed and the apical buds are destroyed. In the presence of ample soil moisture, sprouting is prolific when dormancy is broken. Since land preparation is usually carried out at the onset of the rains, purple nutsedge tubers in infested field are likely to sprout instead of being desiccated to death. Hence the fields remain infested despite the tillage operations. Most of the herbicides used only affect the aerial shoots, just as slashing does, and hence might not effectively eliminate the weed from a field. The methods examined are similar to those employed in the management of the weed and hence the same reason may apply for the non-dependence of the purple nutsedge persistence on the weed management methods.

The type of cropping system and the source of water for irrigation do not directly affect the persistence of the weed though they might have an indirect effect and hence the non-dependence of purple nutsedge persistence on these was expected since they do not have direct effect on the weed.

Like any other plant, purple nutsedge requires ample nutrients for proper growth and development and this might explain why the persistence of the weed was significantly higher with fields that used fertilizers than those which did not. This however does not mean that use of fertilizer will necessarily result in the persistence of the weed as there were some fields which used fertilizers but did not have the weed.

Effect of some environmental factors on prevalence of *Cyperus rotundus*

The environmental factors considered in the study were the agro-ecology of the vegetable fields and the soil properties.

Effect of agro-ecology on the frequency of occurrence and population density of purple nutsedge

Field assessments carried out showed a significant variation in the frequency of occurrence of the purple nutsedge with agro-ecological zones. The weed was significantly higher in the Coastal savannah and Transitional zones than in the Tropical Rainforest and Semi-deciduous forest zones. Between the Coastal savannah and the Transitional zones, the population density of the purple nutsedge was significantly higher for the latter than the former. These two zones gave significantly higher population densities than the Semi-deciduous and Tropical Rainforest zones. Population density for the two forest ecological zones did not show significant differences. The results are presented in Table 32 and Figure 6.

Table 32: Occurrence of purple nutsedge on vegetable fields in the agro-ecological zones

	Presence of purple nutsedge		
Agro-ecological zone	yes	no	Total
Coastal savannah	37 (7.03)	34 (-7.03)	71
Tropical Rainforest	3 (-2.40)	10 (2.40)	13
Semi-deciduous forest	6 (-12.57)	38 (12.57)	44
Transitional zone	19 (8.03)	7 (-8.03)	26
Total	56	98	154

Pearson $\chi^2_{(df=3)} = 29.69$
$p = 0.000$
Figures in parentheses represent unstandardized residuals

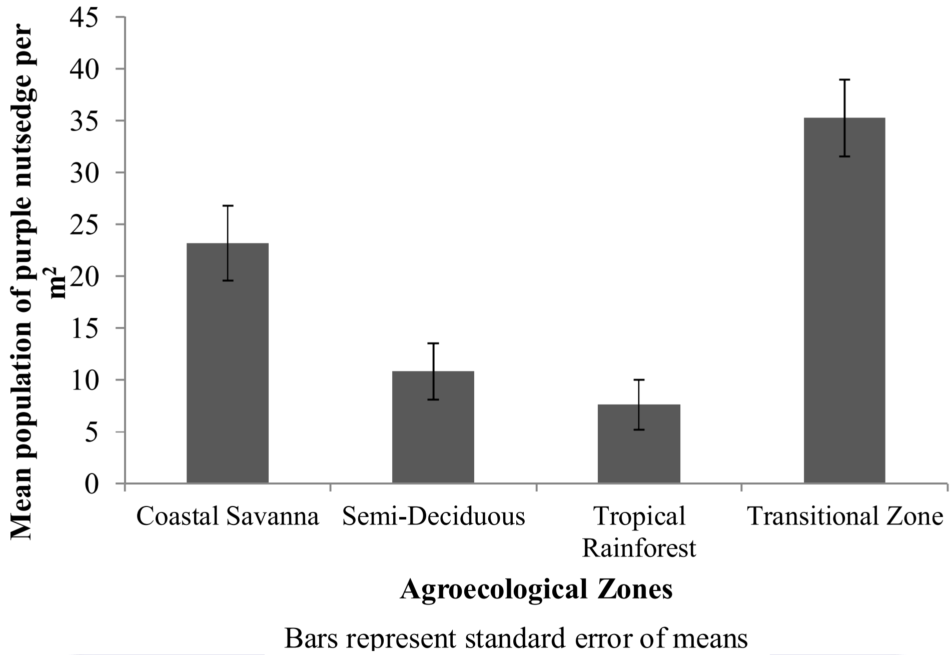


Figure 6: Mean population density of purple nutsedge in vegetable fields of in the agroecological zones of Southern Ghana

Agro-ecological zones are characterized by varied weather conditions including amount and pattern of rainfall, relative humidity, atmospheric temperature and the types of vegetation in the area. The characteristics for the four zones in the study area are indicated in Chapter three.

Both frequency of occurrence and mean population density were significantly lower for the two forest zones than the drier zones (Coastal savannah and Transitional zone). This may be due to the fact that the two forest zones predominantly consist of trees which tend to shade the fields, the shading effect from the trees could limit both occurrence and population density of the weed. Again, the high organic matter composition of the fields in these areas provide ample nutrients for other weeds which rapidly grow taller than the purple nutsedge and suppress its growth by shading. The two drier areas recorded higher frequency of occurrence and population densities probably because they do not have much of tall trees to provide the shade and are also low in organic matter content, hence other weeds present are unable to compete much with the purple nutsedge which can thrive well in all kinds of soils. This argument is confirmed by the fact that majority of the purple nutsedge found in the two forest zones were spotted in areas where trees and tall weeds were limited and soils were poor in organic matter and could hardly support good plant growth.

Correlation between soil physical and chemical properties and the population density of purple nutsedge

The correlations between the various soil parameters and population density of the purple nutsedge are presented in Table 33. Significant negative correlations were observed between the purple nutsedge population density on one hand and the amounts of nitrogen, organic matter, clay and silt on the other hand. The population of the weed was however positively correlated with sand whereas no significant correlation was found with the amounts of phosphorus, potassium and pH level.

Table 33: Correlation between soil properties and purple nutsedge population density

	%N	P (µg/g)	K (cmol/kg)	% OC	% OM	pH	% sand	% clay	% silt
%N	1								
P(µg/g)	.054	1							
K(cmol/kg)	.541**	.198	1						
% OC	.908**	-.034	.505**	1					
% OM	.908**	-.034	.505**	1.000**	1				
pH	-.003	.268	.572**	-.056	-.056	1			
%sand	-.776**	.281	-.395*	-.736**	-.736**	-.054	1		
%clay	.668**	-.265	.510**	.636**	.636**	.278	-.918**	1	
%silt	.738**	-.240	.177	.698**	.698**	-.219	-.886**	.628**	1
weeds	-.678**	.077	-.139	-.585**	-.585**	.218	.611**	-.505**	-.606**

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

The results contradict earlier reports by Iqbal et al. (2012) and Lousada et al. (2013) that purple nutsedge population is positively correlated with nitrogen, phosphorus, potassium and clay contents and negatively correlated with sand content and pH. The results also contradicts expectations that nitrogen should promote its growth and development as reported by Doll (1994). The findings however confirms the earlier arguments that the weed, due to its susceptibility to shading effect from adjacent weeds, seems to prefer depleted soils in the open fields where most plants may not do well. Thus the negative correlation with nitrogen and organic matter may thus, be as a result of the fact that higher nitrogen level encourage the growth of those other weeds which grow rapidly and shade the purple nutsedge. This therefore does not indicate that purple nutsedge prefers soils low in nitrogen and organic matter; it only describes its low inter-specific competitive ability and its ability to do well in poor soils.

Again purple nutsedge is commonly found in sandy soils, especially heaps of abandoned sand, in the study area and this is reflected in the significant positive correlation recorded between the weed and the percentage sand composition of the soil. Apart from the fact that sandy soils generally do not support good growth of weeds, and thus gives the purple nutsedge an upper hand to inhabit such soils, the loose nature of the sandy soils seems to encourage easy sprouting of the purple nutsedge shoots compared to clay and silt which are usually more compacted and hence more difficult to penetrate.

Conclusion

The survey on the agronomic practices carried out on vegetable fields in southern Ghana revealed among other things that land fallowing and bush burning are common practices among farmers even though land fallowing is practiced for shortened periods ranging between six months and four years. The major methods of land preparation included slash and burn and slashing and hoeing. Fertilizer use and irrigation were also common among the farmers with most of the farmers controlling pest and diseases predominantly with pesticides, and weeds with simple tillage implements. First follow up weeding was usually between two and three weeks after planting.

The assessment of the farmers' perception about the purple nutsedge showed that the weed was very popular among the farmers and was locally named after its closest edible relative, the tigernut (*Cyperus esculentus*). Despite its popularity, very little was known about its use. The weed was reportedly present on the fields of more than 50 per cent of the farmers interviewed and was said to be a problem weed all year round, especially in the wet season. It was generally rated as either the worst weed or among the worst by the farmers, who also indicated that it caused serious reduction in crop growth and yield. The major means of control was with the use of herbicides (prior to planting) and by the use of simple tillage implements after planting. These methods were described as moderately adequate.

Among the agronomic practices examined, fertilizer use was found to be the only one that was related to the persistence of the weed. The weed was found to be more prevalent in the Coastal savannah and Transitional zones than in the Tropical Rainforest and Semi-deciduous forest zones. The weed was also found to be negatively correlated with percentage nitrogen, organic matter, clay and silt, and positively correlated with the percentage sand composition. No correlation was however found between the prevalence of the weed, and phosphorus and potassium contents of the soil.

CHAPTER FIVE

MORPHOLOGICAL CHARACTERIZATION OF *Cyperus rotundus* L. IN SOUTHERN GHANA

Introduction

Willis (1988) reported that different biotypes of *Cyperus rotundus* exist at different locations around the world. Subsequent to that, four different subspecies of the weed were identified in East Africa: *C. rotundus rotundus*, *C. rotundus divaricatus*, *C. rotundus merkeri* and *C. rotundus retzii* (Lansdown & Juffe Bignoli, 2013). Variations in a weed species may be caused by mutations, and/or acclimatization to different environments. This results in differences in the biology and ecology of the weed and hence, different biotypes may portray different population dynamics, relate differently to the environment and respond differently to management regimes. The aim of this chapter was first to verify the existence of variations in *C. rotundus* species in the study area, determine if variations are wide enough to cause differences in their population dynamics and, if confirmed, determine the most prevalent biotype to be used for the modelling experiments.

Materials and Methods

Study area

Experiments for the characterization were conducted from January 2016 to March 2016 at the Technology Village of UCC. The facility is situated in the Coastal savannah agro-ecological zone with annual rainfall averaging 800mm with minimum and maximum daily temperatures averaging 22.4^{0}C and 30.6^{0}C respectively.

Layout and Experimental Design

Purple nutsedge collection for the experiment consisted of a total of 46 samples: 40 samples collected from 40 localities across the study area and three from each of the two experimental fields used for the determination of parameters for the model (Chapter Seven). Tubers of the collection were first planted separately in plastic pots filled with loamy soil (described in Chapter Three) and left for 3 months in order for them to multiply. The pots were watered regularly and other emerged weeds ridded off by hand picking. Subsequently, the mature tubers were transferred into 28cm diameter plastic pots with depth 15cm for the experiment. The experiment was laid out in a Completely Randomized Design with three replications. The treatments were imposed by planting four tubers per pot. The pots contained a mixture of loam sand and decomposed poultry manure which was mixed in the ratio 4:1:1.

Data collection

The growth of the samples was observed and characterized based on both underground and above ground (including inflorescence) characteristics on five randomly selected mature tubers and shoots as follows:

- Skin colour of mature tuber:

  This was rated on a scale of 1 (brown) to 10 (black) with the aid of a colour chart

- Shape of mature tuber:

  This was scored on a nominal scale of oval (1), oblong (2), ovoid (3), elliptical (4), round (5), cylindrical (6) as described by the Canadian Food Inspection Agency (2013)

- Diameter of mature tuber:

  This was taken with the aid of a calliper from the middle portion of the tuber

- Length of mature tuber:

  This was taken with the aid of a calliper from the proximal to the distal ends of the tuber

- Width of basal bulb:

  This was taken with the aid of a calliper from the middle portion of the bulb

- Number of shoots per m^2 :

  This was taken weekly as described in Chapter 3

- Shoot height at maturity:

  This was taken with the aid of metre rule from soil level to the highest point of the plant in it natural orientation

- Number of leaves per plant:

This was counted as the total number of true leaves on the plant (excluding bracts) including both dried and fresh ones

- Leaf angle:

  This was observed on the third leaf from the base of the shoot on a scale of 1(horizontal) to 10 (vertical) when compared to a template of 10 lines converging at 90 intervals from horizontal to vertical.

- Colour of leaf base:

  This was rated on a scale of 1 (light) to 10 (dark) green with the aid of a colour chart

- Colour of leaf laminar:

  This was rated on a scale of 1 (light) to 10 (dark) green with the aid of a colour chart

- Stem diameter:

  This was taken with the aid of a calliper as the diameter of the shoot at ground level

- Culm length:

  This was measured with the aid of a meter rule as the distance between the point where the culm emerges and the highest point on the culm in its natural orientation

- Length of longest leaf per shoot:

  This was taken as the distance between the base of the longest leaf to the leaf apex with the aid of a rule.

- Width of widest leaf per shoot:

This was taken as the distance from end to end of the leaf margins, perpendicular to the mid-rib at the widest portion of the leaf

- Length, longest seed spikelet:

  This was measured as the distance between the base and the tip of the spikelet with a rule

- Number of rachises per inflorescence:

  This was counted by direct observation

- Length, longest rachis:

  This was measured as the distance between the base and the tip of the rachis with a rule

- Number of involucral bracts per inflorescence:

  This was counted by direct observation

- Length, longest involucral bract:

  This was taken as the distance between the base of the longest bract to the apex with the aid of a rule.

- Width widest involucral bract:

  This was taken as the distance from end to end of the bract margins, perpendicular to the mid-rib at the widest portion of the bract

- Inflorescence colour:

  This was rated on a scale of 1 (light) to 10 (dark) purplish-brown

Data Analyses

The qualitative data collected were first summarized by simple frequencies and then analysed by the chi-square test of independence for their dependence on the four agro-ecological zones. The quantitative data collected were described with appropriate measures of central tendency and dispersion and then analysed by analysis of variance with respect to the agro-ecological zones. They were then subjected to Pearson's correlation analysis to help in scaling down the number of characters for the multivariate analysis. A total of eleven characters, including both quantitative and qualitative characters were first standardized by dividing each data point by the maximum data point for the respective characters in order to scale the entire data between 0 and 1 and then used for the Principal Component Analysis which was based on the sum of squares and products. These eleven characters were further subjected to the hierarchical cluster analysis with complete link methods. The qualitative data were subjected to the simple matching test while the quantitative data were subjected to the Euclidean test to form the similarity matrix prior to the cluster analysis. The data was analysed with the aid of GenStat Discovery Edition 4.

Results

Variation in qualitative characters

Skin colour of mature tubers

The skin colour of mature tubers ranged from 7 to 10 on a scale of 1 (brown) to 10 (black) (Figure 7), with 8 and 9 recording the highest percentage frequencies of 40.4% each. The least was recorded by 10 with 1.8%, followed by 7 which recorded 17.5 %.

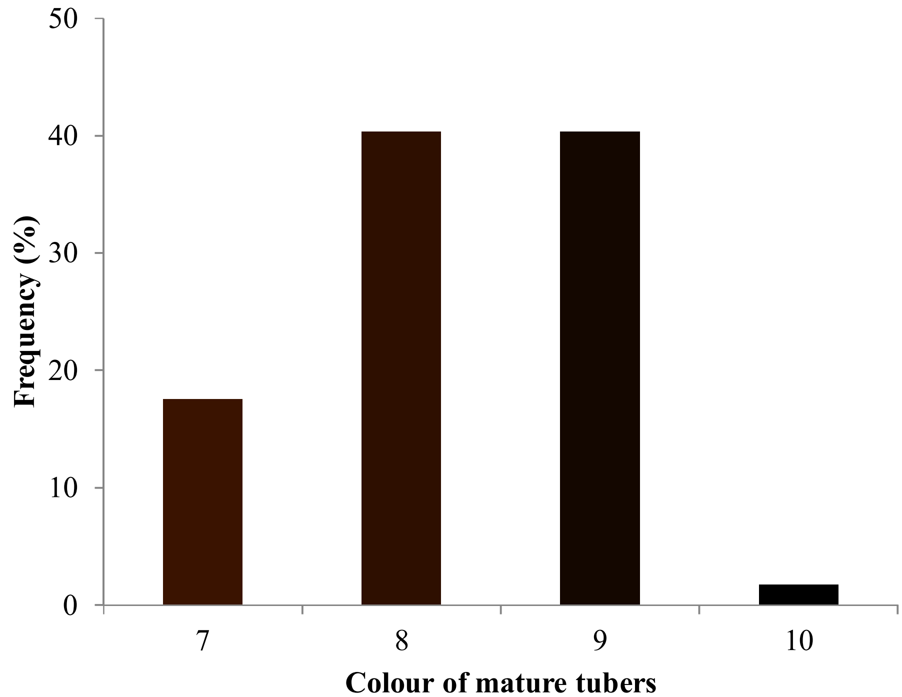


Figure 7: Frequency of colour of mature tubers of purple nutsedge

Colour of leaf base

The colour of the leaf bases of the shoots ranged between 2 and 5 on the scale of 1 (light green) to 10 (green black) with the highest percentage frequency of 57.4% recorded by 3 (Figure 8). This was followed by 2 which recorded 34.0% and 4 and 5 which recorded 6.4% and 2.1% respectively.

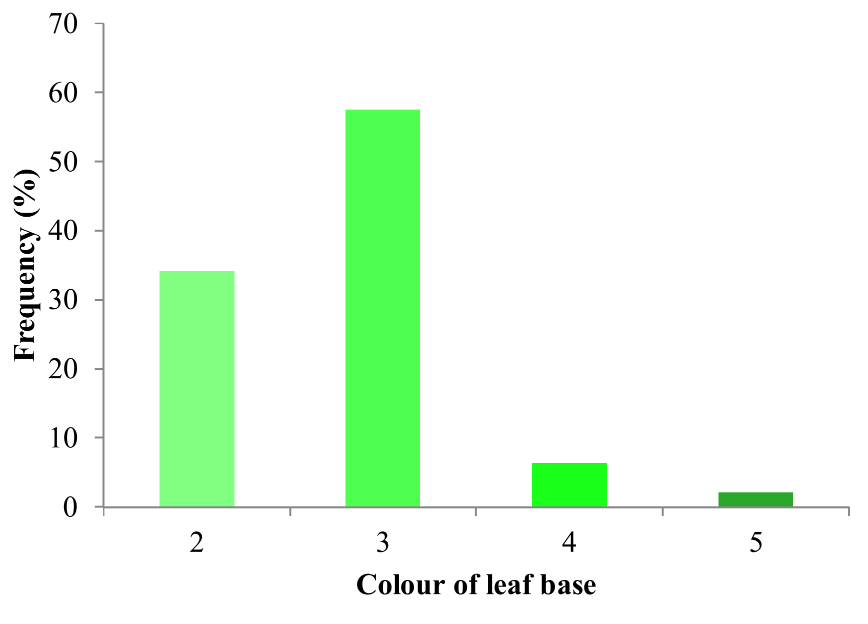


Figure 8: Frequency distribution of colour of leaf base of purple nutsedge

Colour of leaf lamina

Generally, the laminas of the leaves were greener than the bases. The colour recorded ranged from 3 to 7 on the same scale of 1 to 10 (the same for the leaf base) (Figure 9). The least percentage frequency recorded of 2.1% was recorded for 3, and this was followed by 7 with 14.9%. The others were 5 which recorded a percentage frequency of 36.2%, and 6 which recorded the highest percentage frequency of 46.8%.

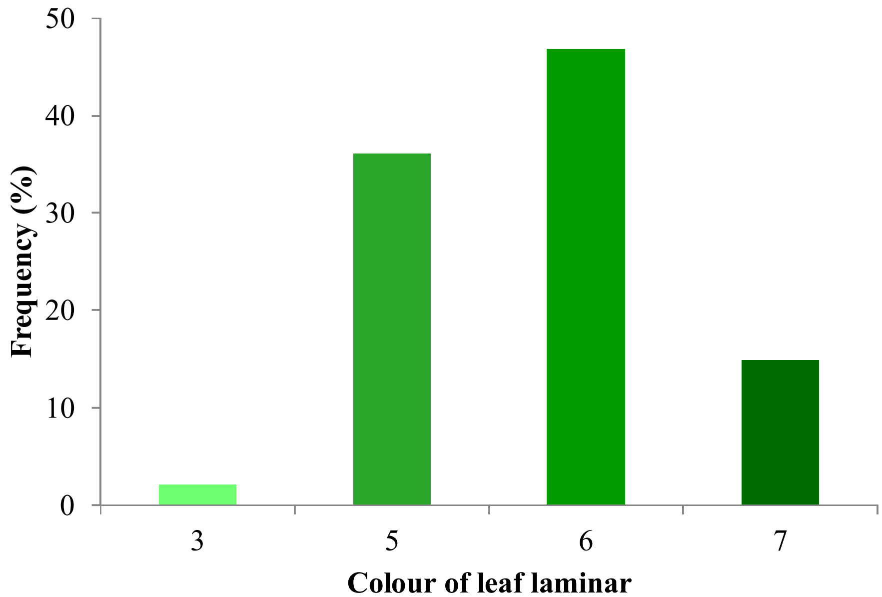


Figure 9: Frequency distribution colour of leaf laminar of purple nutsedge

Colour of inflorescence

The highest percentage frequency of 55.3% for the inflorescence colour was recorded by 8, followed by 7 with 25.5%, 9 with 14.9% and 6 with 4.3%. (Figure 5.4)

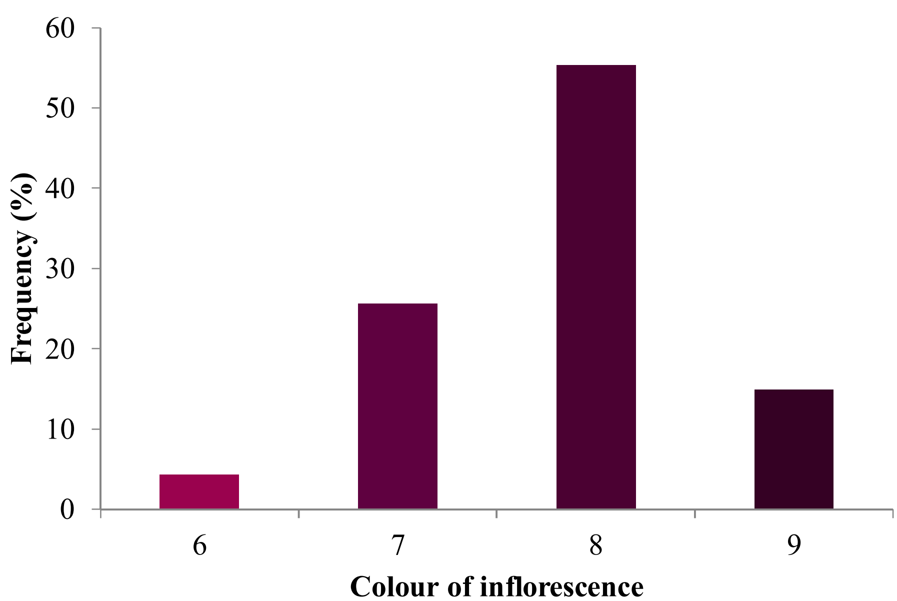


Figure 10: Frequency distribution of purple nutsedge inflorescence colour

Leaf angle

Leaf angle measured ranged between 4 and 8 with 6 recording the highest percentage frequency of 42.6% this was followed closely by 7 with frequency percentage of 40.4%. The least percentage frequency of 2.1% was recorded by 4. Figure 11 shows the results

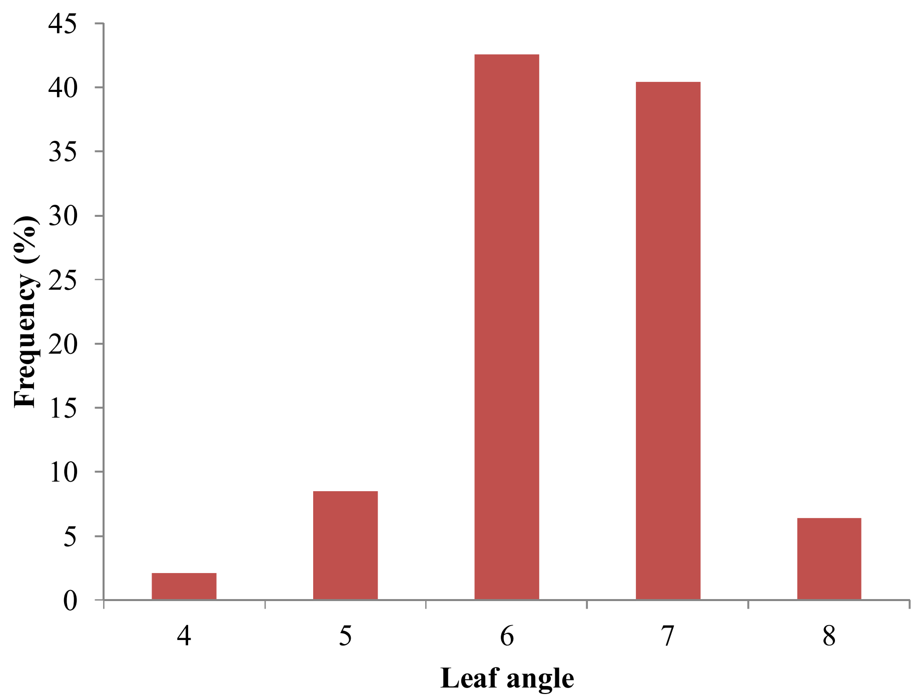


Figure 11: Frequency distribution of leaf angle of purple nutsedge

Shape of mature tubers

The mature tubers varied in their shapes with the highest proportion of 28.1% taking the elliptical shape, followed by the ovoid and oval shapes taken by 21.1% each. The least frequency percentage of 3.5% was recorded by the tubers with the cylindrical shape. The result is presented in Figure 12.

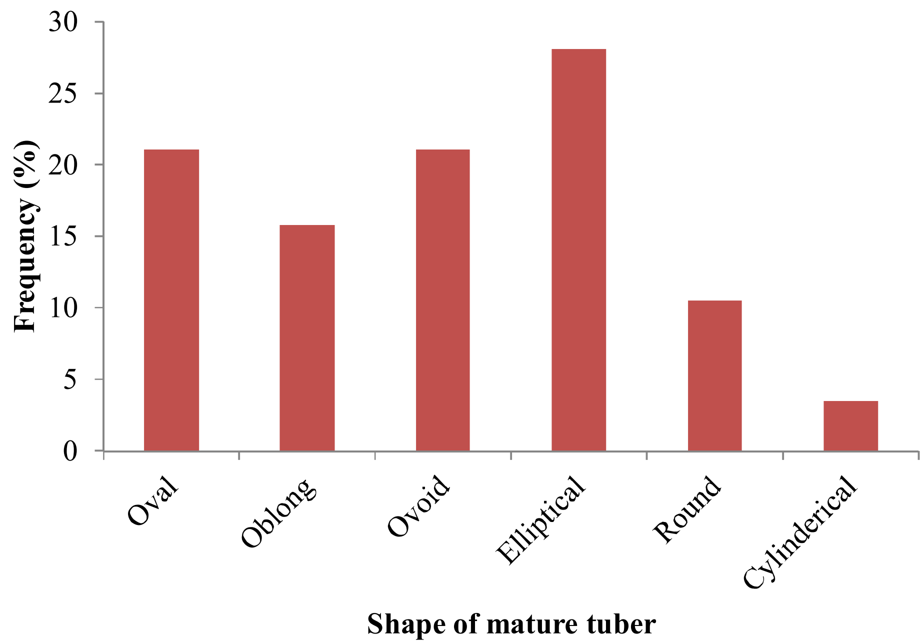


Figure 12: Frequency distribution of shape of mature tubers of purple nutsedge

Variation of qualitative traits with agroecological zones

The chi-square test of independence did not show significant variation with the agroecological zones in respect of skin colour of mature tubers, shape of mature tubers, colour of leaf base, colour of leaf laminar, colour of inflorescence and leaf angle respectively (Table 34).

Table 34: Chi-square test of independence for dependence of qualitative characters on agroecological zones

Qualitative trait	χ^2	df	P-value
Skin colour of mature tubers	2.7	9	0.98
Shape of mature tubers	23.76	15	0.07
Colour of leaf base	3.92	9	0.98
Colour of leaf laminar	10.47	9	0.31
Colour of inflorescence	11.32	9	0.26
Leaf angle	6.83	12	0.87

Variations in quantitative characters measured

Descriptive statistics of quantitative characters measured

The quantitative characters considered included underground characteristics, vegetative shoot characteristics and inflorescence characteristics. Among the underground characteristics, diameter of mature tubers ranged from 5.28 mm to 10.45 mm with a mean of 8.14 mm and standard deviation of 1.22. Length of mature tuber had a mean of 13.66 mm with a standard deviation of 3.57 and ranged from 7.48 mm to 26.23 mm. The basal bulb diameter ranged from 4.29 mm to 10.41 mm with a mean of 6.38 mm and standard deviation of 1.45.

Among the vegetative shoot characters, height of the purple nutsedge shoot ranged from 15.60 cm to 38.50 cm and had a standard deviation of 5.84, with number of leaves ranging from 5 - 16 per plant, averaging 11.26 with standard deviation of 2.91. The longest leaf per plant ranged from 15.50 cm to 35.70 cm with a mean of 23.87 cm and standard deviation of 5.06.

Data collected on the inflorescence characters gave the length of longest seed spikelet, number of rachises per inflorescence and the length of the longest rachis as 11.84 mm, 4.32 and 3.49 cm respectively with their respective standard deviations as 2.86, 0.59 and 1.05. The length of longest seed spikelet recorded ranged from 6.00 mm to 16.00 mm whereas the number of rachises per inflorescence was within the range of 3 and 5. The maximum length of longest rachis was 1.70 mm with 6.10 mm as the minimum. The descriptive statistics of the quantitative characters measured are presented in Table 35.

Table 35: Descriptive statistics of quantitative characters measured

	Mean	Std Error	Std Deviation	Min	Max	Confidence Level(95.0%)
Diameter of mature tuber	8.14	0.16	1.22	5.28	10.45	0.32
Length of mature tuber	13.66	0.47	3.57	7.48	26.23	0.95
Diameter of basal bulb	6.38	0.21	1.45	4.29	10.41	0.42
Shoot height at maturity	26.81	0.85	5.84	15.60	38.50	1.72
No. of leaves per plant	11.26	0.42	2.91	5.00	16.00	0.85
Fascicle girth	3.01	0.10	0.65	2.06	4.33	0.19
Culm length	19.20	0.76	5.21	9.00	31.00	1.53
Length, longest leaf per shoot	23.87	0.74	5.06	15.50	35.70	1.49
Width, widest leaf per shoot	5.16	0.10	0.68	4.00	7.00	0.20
Length, longest seed spikelet	11.84	0.42	2.86	6.00	16.00	0.84

	Mean	Std Error	Std Deviation	Min	Max	Confidence Level (95.0%)
Rachises per inflorescence	4.32	0.09	0.59	3.00	5.00	0.17
Length, longest rachis	3.49	0.15	1.05	1.70	6.10	0.31
No. of Involucral bract per inflorescence	3.34	0.11	0.73	2.00	4.00	0.21
Length, longest involucral bract	6.52	0.31	2.11	3.50	13.50	0.62
Width widest involucral bract	3.91	0.11	0.73	3.00	6.00	0.21

Comparison of quantitative characteristics of purple nutsedge from the four agroecological zones

The quantitative characters were assessed for variation with the four agro-ecological zones (Table 36). Considering the underground characters, purple nutsedge tubers from the Transitional zone recorded the least diameter of 5.43 mm and this was significantly different ($p < 0.05$) from the other zones. No significant differences were observed in the diameter of mature tubers from the other zones ($p > 0.05$). The other underground characters, length of mature tubers and width basal bulb, did show significant differences ($p > 0.05$) with respect to the agro-ecological zones even though the Transitional zone recorded the highest length of mature tubers with 14.61 mm with the Coastal savannah recording the lowest length of mature tubers. For the width of basal bulb, the Semi-deciduous forest zone had the highest diameter of 7.34 mm followed by the Coastal savannah, Tropical Rainforest and lastly the Transitional zone in that order.

Table 36: Comparison of underground characteristics of purple nutsedge from four agro-ecological zones of southern Ghana

Agro-ecological zone	Diameter of mature tuber (mm)	Length of mature tubers (mm)	Diameter of basal bulb (mm)
Coastal savannah	8.37a	12.90	6.37
Tropical Rainforest	8.03a	13.64	6.32
Semi-deciduous forest zone	8.66a	13.06	7.34
Transitional zone	5.43b	14.61	5.81
Standard error	0.60	2.17	0.89
%CV	14.82	26.64	22.65

In terms of vegetative above-ground characters, the Tropical Rainforest zone recorded the highest in terms of height of shoot at maturity of 35.75 cm and this was significantly different ($p < 0.05$) from those of the Semi-deciduous forest (24.48 cm) and transitional (24.33 cm) zones but not significantly different from the Coastal savannah zone which recorded a mean height of 27.32 cm (Table 37).

Significant differences were also observed ($p < 0.05$) with the number of leaves per shoot with those from Transitional zone recording the lowest mean of 5.33 which was significantly different from all the others. Significant differences were however not observed between the other three zones.

The girth of fascicle of the purple nutsedge also differed significantly with the agro-ecological zones ($p < 0.05$). The highest girth was recorded by collections from the Semi-deciduous forest zone which gave a mean fascicle girth of 3.27 mm followed by the Coastal savannah with 3.05 mm, the Tropical Rainforest 2.31 mm and finally the Transitional zone with 2.28 mm. Significant differences were observed between the Semi-deciduous forest zone and the Transitional zone.

A trend similar to that of the fascicle girth was observed for the length of the longest leaf: the highest was recorded by the Semi-deciduous forest zone followed by the Coastal savannah, Tropical Rainforest and the Transitional zone in that order recording 25.84 cm, 23.71 cm 24.50 cm and 16.87 cm respectively. No significant difference were observed between the first three, however, they all differed significantly from the Transitional zone.

A different trend was observed for the girth of the culm where the highest girth of 28.9 cm was recorded by the Tropical Rainforest and was significantly different from those from the other zones. Differences were however not significant among the Coastal savannah, Semi-deciduous forest and the Transitional zones which recorded 19.61 mm, 16.59 mm and 16.00mm respectively.

The width of the widest leaf also differed significantly with the agro-ecological zones with the Semi-deciduous forest zone recording the highest width of 5.61 mm and closely followed the Transitional zone with 5.33 mm. While these two were not significantly different, they differed significantly from the Coastal savannah which recorded 5.07 mm and the Tropical

Rainforest which recorded 4.00 mm and were also significantly different from each other.

Table 37: Comparison of shoot quantitative characteristics of purple nutsedge from the four agro-ecological zones

Agro ecological zone	Height of shoot at maturity (cm)	Number of leaves per shoot	Girth of fascicle (mm)	Girth of culm (mm)	Length of longest leaf (cm)	Width of widest leaf (mm)
Coastal savannah	27.32ab	12.10a	3.05a	19.61b	23.71a	5.07b
Tropical Rainforest	35.75a	11.67a	2.31ab	28.90a	24.50a	4.00c
Semi-deciduous forest zone	24.48b	10.58a	3.27a	16.59b	25.84a	5.61a
Transitional zone	24.33b	5.33b	2.28b	16.00b	16.87b	5.33ab
Standard error	3.38	0.22	0.37	2.70	2.90	0.35
%CV	21.79	25.83	21.37	27.14	32.44	13.21

With the inflorescence characteristics, three of the characters: number of rachises, number of involucral bracts and the length of the longest involucral bracts, did not differ significantly ($p > 0.05$) with the agro-ecological zones (Table 38). The highest number of rachises was recorded by collections from the Semi-deciduous forest zone with a mean of 4.67 with the Coastal savannah recording the least with 4.21. The highest number of involucral bracts of 3.67 was recorded for both the Semi-deciduous forest and the Transitional zones with the Tropical Rainforest recording the least of 2.67.

The Transitional zone also recorded the highest length of involucral bract of 8.17 mm whereas the least of 6.27 mm was recorded by the Semi-deciduous forest zone.

Considering the longest spikelets, the Tropical Rainforest recorded 15.17 mm, but this was not significantly different from those of Coastal savannah and Transitional zones which recorded 12.17 mm and 12.67 mm respectively. All three however, differed significantly from the Semi-deciduous forest which recorded a mean length of 10.00 mm.

Again the highest length of longest rachis of 4.80 mm was recorded by the Tropical Rainforest and this was significantly different from the Transitional zone (3.83 mm), Coastal savannah (3.49 mm) and the Semi-deciduous forest zone (3.09 mm). The last three did not differ significantly from each other.

Finally, width of the widest involucral bract saw the Transitional zone recording the highest width of 5.33 mm and differing significantly from the other three which recorded 4.08 mm, 3.76 mm and 3.33 mm respectively for Semi-deciduous forest, Coastal savannah and Tropical Rainforest. The latter three did not differ significantly from each other.

Table 38: Comparison of inflorescence quantitative characteristics of purple nutsedge from the four agroecological zones

Agro ecological zone	Length of longest spikelet (mm)	Number of rachises	Length of longest rachis (cm)	Number of involucral bracts	Width of widest involucral bract (mm)	Length of longest involucral bract (cm)
Coastal savannah	12.17a	4.21	3.49b	3.24	3.76b	6.58
Tropical Rainforest	15.17a	4.00	4.80a	2.67	3.33b	5.23
Semi-deciduous forest zone	10.00b	4.67	3.09b	3.67	4.08b	6.27
Transitional zone	12.67a	4.33	3.83b	3.67	5.33a	8.17
Standard error	1.59	0.11	0.61	0.08	0.37	1.28
%CV	24.12	13.75	30.09	21.87	18.63	32.44

Correlation between the quantitative characters measured

The correlations analysis between the various quantitative parameters measured was carried out to facilitate the cluster analysis of the collection (Table 39). The highest correlation coefficient of 0.951 was observed between culm length and height of plant at maturity and this was highly significant ($p<0.01$). Other high correlation coefficients were observed between fascicle girth and diameter of basal bulb ($r = 0.508$, $p < 0.01$), and length of longest spikelet and shoot height at maturity (r = 0.53, p < 0.01). The others were between length of longest rachis on one hand and shoot height at maturity (r = 0.648, p < 0.01), culm length (r = 0.610, p < 0.01) and length of longest seed spikelet (r = 0.774, p < 0.01) on the other hand.

No significant correlations were found between length of mature tubers and width of widest leaf (r = 0.000, p = 0.998), diameter of mature tuber and shoot height at maturity (r = 0.008, p = 0.959) and length of longest rachis and number of involucral bracts (r = 0.002, p = 0.987).

Principal component analysis of collections with morphological traits

The principal component analysis of the 46 purple nutsedge collections from southern Ghana was carried out with 11 out of the 21 morphological characters (Table 40). These were chosen after a careful examination of the correlation matrix. The analysis grouped the characters into four latent factors which accounted for a total of 82.80% of variations observed with PC1, PC2, PC3 and PC4 accounting for 43.94%, 20.49% 10.20 and 8.17% respectively.

The highest contribution to PC1 came from length of longest involucral bract with an absolute contribution of 0.821. This was followed by number of leaves per plant with 0.242 and shoot height at maturity with 0.237. PC1 had a latent root of 7.755. Length of longest seed spikelet contributed an absolute value of 0.507 to PC2, recording the highest contribution. Other important contributors included length of longest rachis (0.474) the culm length, (0.429). The number of leaves per plant and the fascicle girth were the major contributors to the PC3 with 0.593 and 0.430 respectively.

Table 39: Correlation between quantitative characters measured on various collections of purple nutsedge

	DMT	LMT	DBB	SHM	NLP	FAG	CUL	LLL	WWL	LLS	NRI	LLR	NIB	LLI	WWI
DMT	1														
LMT	.164	1													
DBB	.124	-.065	1												
SHM	.008	-.126	.086	1											
NLP	.449**	-.170	.320*	-.265	1										
FAG	.108	-.058	.508**	-.163	.406**	1									
CUL	.073	-.093	.104	.951**	-.178	-.197	1								
LLL	.120	-.037	.061	.374**	-.059	.312*	.320*	1							
WWL	-.176	.000	.094	-.279	.112	.453**	-.390**	.020	1						
LLS	-.146	-.201	.166	.530**	-.071	-.171	.541**	-.274	-.142	1					
NRI	-.097	.194	.068	.280	-.313*	.109	.168	.202	.140	-.046	1				
LLR	-.157	-.194	.174	.648**	-.234	-.191	.610**	-.039	-.019	.774**	.099	1			
NIB	-.112	.071	.021	-.045	-.277	.227	-.153	.114	.085	-.036	.396**	-.002	1		
LLI	-.310*	-.072	-.095	.475**	-.432**	.040	.332*	.380**	-.173	.091	.462**	.196	.485**	1	
WWI	-.492**	-.034	-.043	.128	-.587**	-.052	-.017	.075	.180	.017	.292*	.213	.449**	.511**	1

DMT: Diameter of mature tuber; LMT: Length of mature tuber; DBB: Diameter of basal bulb; SHM: Shoot height at maturity; NLP: No. of leaves per plant; FAG: fascicle girth; CUL: Culm length; LLL: Length, longest leaf per shoot; WWL: Width, widest leaf per shoot; LLS: Length, longest seed spikelet; NRI: Rachises per inflorescence; LLR: Length, longest rachis; NIB: Number of involucral bracts; LLI: Length, longest involucral bract WWI: Width widest involucral bract

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table 40: Principal component analysis showing contributions of morphological characters to variations in purple nutsedge collection

Variables	PC1	PC2	PC3	PC4
Colour of leaf base	0.138	-0.047	0.096	0.104
Culm length	-0.206	-0.429	-0.277	-0.189
Length of longest involucral bract	-0.821	0.247	-0.121	-0.022
Length longest leaf per shoot	-0.138	0.092	-0.422	-0.224
Length longest rachis	-0.164	-0.474	0.122	0.286
Length longest seed spikelet	-0.109	-0.507	0.115	0.439
Number of Involucral bract per inflorescence	-0.223	0.302	0.219	0.509
Number of leaves per plant	0.242	0.012	-0.593	0.370
Shoot height at maturity	-0.237	-0.346	-0.219	-0.138
Fascicle girth	0.011	0.205	-0.430	0.450
Width widest involucral bract	-0.203	0.095	0.247	0.105
Latent roots (Eigen Values)	7.755	3.617	1.801	1.442
Percentage Variation	43.94	20.49	10.20	8.17
Cumulative % Variation	43.94	64.43	74.63	82.80

Cluster analysis of collections

The similarity coefficients for the cluster analysis ranged from 0.5 (dissimilar) to 1.0 (similar). At 0.5 similarity coefficient, all the 48 collections were put into one cluster, however at 0.7, they further divided into four clusters. The four clusters each comprised collections from the various agro-ecological zones suggesting the clustering did not depend on agro- ecological conditions (Figure 13).

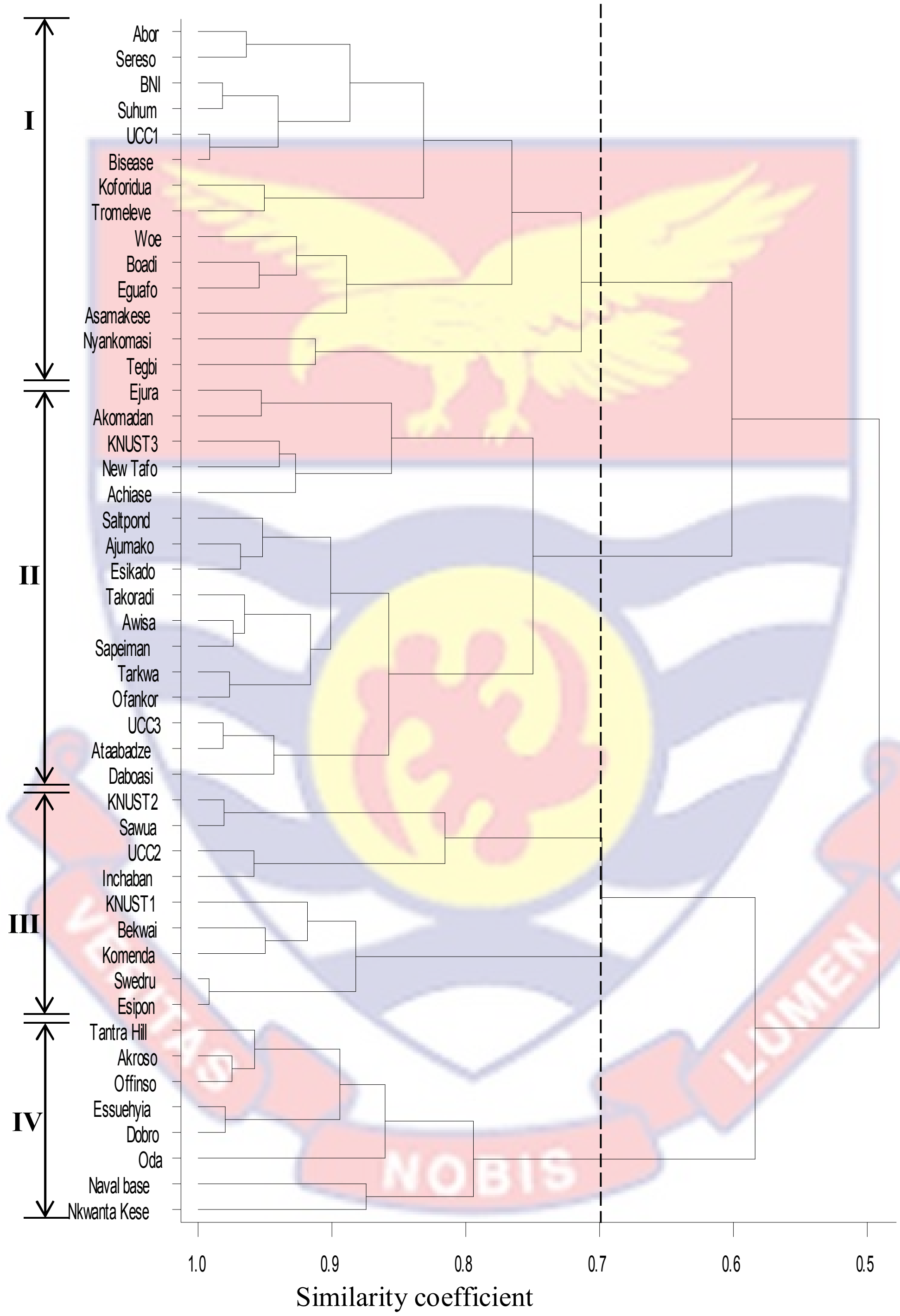


Figure 13: Dendrogram of the purple nutsedge collection based on morphological characters cut at 0.7 similarity coefficient

Discussion

Morphology of purple nutsedge from southern Ghana

The morphology of purple nutsedge from the study area, southern Ghana, is described by Figures 7 to 12 and Table 35. Generally, the descriptions confirm what has been described earlier (Riemens et al., 2008; Stoller & Sweet, 1987; Willis, 1987): dark brown to black mature tubers, elliptical, ovoid, oval, oblong round or cylindrical in shape, light to deep green leaves and leaf bases, dark purple to purple brown inflorescence. A major deviation was however observed with the absence of the rachilla, a structure which was reported to be present in all samples collected from around the world by Willis (1988). This deviation may be as a result of the ecotypic variation as reported by Willis (1987)

With the quantitative characters, the mean culm length and length of longest leaf per shoot recorded for the collections compared lower to those recorded by Willis (1988) for his collections from around the world. The mean number of leaves and the width of widest leaves however, were within the range reported by the same author.

Variation of characters with agro-ecological zones

The various qualitative characters considered: colour and shape of mature tubers, colour of leaf laminar and leaf bases, leaf angle and colour of inflorescence, together with some tuber and inflorescence characters (length of mature diameter, diameter of basal bulb, numbers of rachises and involucral bracts and length of longest involucral bracts) did not vary with agro-ecological zones. This may point to minimum variation in the samples collected. However, the significant differences observed for all the vegetative shoot characters, diameter of mature tuber and three of the inflorescence characters also suggest some variations in the samples with the agro-ecological zones. These differences may be the result of morphological and/or physiological adaptions to the various agro-ecological conditions. Adaptations to different agro-ecological conditions in purple nutsedge have been reported by Pena-Fronteras et al. (2008) and Jha and Sen (1980). These adaptions serve as survival mechanisms for the weed under the respective conditions, particularly rainfall pattern and distribution, and soil characteristics. They also enhance their competitive ability and give them the ability to compete well with crops on vegetable fields.

Factor and cluster analysis of purple nutsedge collection

The principal component analysis gave four latent factors, PC1, PC2, PC3 and PC4, as the major components determining variations in the collections. A close examination of the factor loadings showed that the major contributor to the PC1 was the length of the longest involucral bract. This was followed by number of leaves per shoot, the number of involucral bracts, shoot height at maturity and the culm length. These characters together seem to point to the photosynthetic structures of the plant since they mostly involve involucral bracts, leaves and height and all these seem to contribute to improved photosynthesis. Thus the first and most important component for classification of purple nutsedge in southern Ghana may comprise the photosynthetic structures that is, involucral bracts and leaves, of the weed.

For PC2, the highest contributions came from the length of longest seed spikelet, followed by length of longest rachis, culm length and shoot height at maturity. All these contribute significantly to the total plant height at maturity (Table 39) and thus PC2 may be described in terms of plant height.

The third principal component (PC3) which accounts for 10.20 per cent of the total variation consists mainly of number of leaves per plant, fascicle girth and the length of the longest leaf per shoot. All these characters are encompassed in leaf characteristics and therefore this may be considered as the third most important factor.

The last component, PC4 consist mainly of the number of involucral bracts, the length of the longest seed spikelet, the fascicle girth and the number of leaves. These do not seem to point to any particular trend or tangible factor and may hence be considered as a miscellaneous grouping of variables.

The dendrogram in Figure 5.6 shows four major clusters when cut at 0.7 similarity coefficient. These four clusters did not show any trend with respect to the locational sources of the samples nor their original agro-ecological zones. For example, in cluster I, Abor, UCC1 and BNI all happen to be in the Coastal savannah, whereas Suhum, Sereso and Koforidua are in the Semi-deciduous forest zone, with Tromeleve in the Transitional zone. The same is seen for the other clusters where the locations involved occur in different agro-ecological zones. UCC1, UCC2 and UCC3 were expected to be in the same cluster if clustering had anything to do with agro-ecological zones, yet they occur in clusters I, III and II respectively.This indicates that the clustering was not based on locations and/or agro-ecological zones and point to the fact that on the whole, differences observed among the samples were not relative to the locations from which they were picked. This is buttressed by the fact that the PCA analysis gave the length of the longest involucral bract as the most important variable and this was seen not be significantly differ from with the agro-ecological zones.

Conclusion

The study showed general a conformation of the purple nutsedge in southern Ghana to those described from other part of the world, except for the absence of rachilla. Significant variations were observed between agro-ecological zones for a number of the quantitative variables. This variation suggests some form of morphological adaptation to agro-ecological conditions such as rainfall and soil characteristics. The other characters measured did not vary with agro-ecological zones. The major factors which determined differences in purple nutsedge in the study area were photosynthetic structures (involucral bracts and leaves), plant height and leaf characteristics. The collections were grouped into four major clusters but these were not with respect to locational sources of the weed nor their agro-ecological zones despite the fact that some of the morphological characters considered differed significantly with agro-ecological zones.

CHAPTER SIX

MODEL CONCEPTUALIZATION

Introduction

This Chapter commences the process of model formulation using the available information gathered in the previous chapters. The chapter looks specifically at the system to be modelled and the modelling procedure used. It is often called the conceptual modelling phase (Jackson et al., 2000) and comprises both diagrammatic and mathematical representation of the system. The chapter first combines the information gathered, examines it critically and then summarizes the processes that occur in the ecosystem of the *Cyperus rotundus* L within the vegetable field and presents it diagrammatically for clearer understanding. It further specifies necessary assumptions and degrees of complexity in terms of space, time and random events. It then translates the concept into mathematical relationships in a process often called Mathematical formulation. The Chapter is concluded after examining the model's strengths and identifying knowledge gaps and other problems associated with the chosen modelling procedure.

System Analysis

The system is an agro-ecosystem and comprises the object of study and its regulating factors (Brak, 2009). The object of study here is the population of shoots and tubers of *C. rotundus* and the regulating factors include the weather of the study area (southern Ghana), weed management measures employed in the control of the weed, and other organisms in the agro-ecosystem, basically the vegetable crop (assuming no other weeds are present in the system). In the absence of the regulating factors, *C. rotundus* exhibits its own intrinsic population dynamics with respect to its life cycle, and this is modified by the regulating factors (Cousens & Mortimer, 1995) (Figure 14). This section examines both the intrinsic population dynamics of the weed and how it is affected by the external factors.

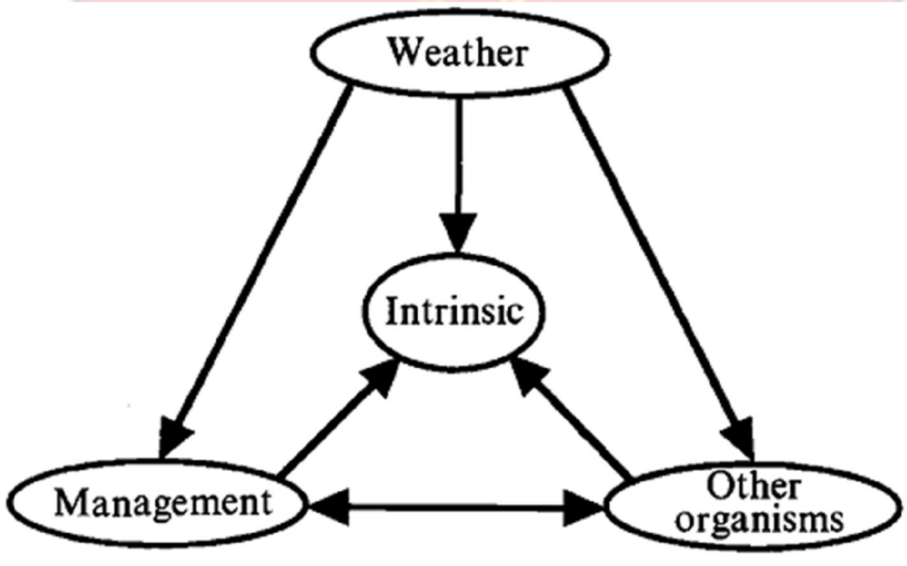


Figure 14: Diagrammatic representation of the interaction between weed intrinsic population and external factors (adapted from Cousens and Mortimer, 1995)

Recap of intrinsic life history of *Cyperus rotundus* L.

As indicated by Stoller and Sweet (1987), the purple nutsedge initiates its life cycle from tubers which comprise it major propagating material (since viable seeds hardly occurs). A sharp pointed rhizome sprouts from the tuber bud (when conditions are favourable) and grows toward the soil surface where it forms the subterranean basal bulb. The bulb then develops fibrous roots and the shoot which initially consist basically of the leaves. The basal bulb then gives off secondary rhizomes which also develops into the secondary basal bulbs and continue to produce new shoots. The cycle continues for a period of time until the shoots begin to flower. After flowering, the purple nutsedge undergoes a marked shift from aboveground to below ground development, so that tubers continue to form for several weeks. The tubers produced add up to the tuber load in the soil for the next cropping season even though a proportion of the load remains dormant.

Modifications to this basic cycle exist. First, tuber mortality (both natural and artificially induced) and tuber dormancy are two important factors that affect viable tuber load in the field. Again, increased tuber load density may result in intra-specific competition and alter the sprouting rate of tubers. Further, the biotypic variations described by various writers (Pena-Fronteras et al., 2008; Willis, 1987, 1988) may result in an altered life history from this basic one.

Impact of some environmental conditions on *Cyperus rotundus* L.

The major environmental factors that influence the life cycle of the purple nutsedge are temperature, soil moisture and light (both duration and intensity). However temperature and light duration are not major factors in the study area since it happens to be in the tropics where temperature is relatively high and less variable compared to the temperate regions (Horowitz, 1992).

Soil moisture greatly affects the survival, viability and sprouting of the purple nutsedge. These three properties increase with increasing soil moisture content until an optimum level is reached and then begins to decline (Horowitz, 1992). Unlike desiccation (extreme dryness), which can completely kill purple nutsedge tubers, flooding (extreme wetness) may only reduce sprouting. The relationship between moisture on one hand and tuber survival, viability and sprouting, on the other hand, thus begins with a sigmoid shape, declining after the maximum level is attained and then levels off after sometime of decrease.

Purple nutsedge has the ability to grow and spread rapidly in high light levels because it possesses the C_4 dicarboxylic acid photosynthetic pathway. The shoot and tuber production of the weed is thus highly positively correlated with the intensity of photosynthetically active radiation. Shading thus greatly reduces the number and size of tubers and shoots produced but does not kill them (Stoller & Sweet, 1987; Willis, 1987). The relationship between light intensity and shoot production thus may be linear. Natural day length, as it occurs in the vegetable fields of southern Ghana, has no effect on tuberization in purple nutsedge.

The weed is known to tolerate soils of various characteristics; however it is significantly improved by soil nutrients. The performance of the weed with respect to soil types was unclear but has been clarified (Table 33). Most tubers occur within the top 15cm of the soil. Within this depth, sprouting does not depend on the depth of burial as reported by Haizel and Bennett-Lartey (1986); exposure to dessication (when tubers are brought to the soil surface) may rather increase mortality and/or reduce sprouting rate.

Impact of crops and weed management methods on *Cyperus rotundus* L

The other factors that affect the weed population are the competition from other plants and the management methods employed by the farmer. The magnitude of inter-specific competitive effect of the vegetables on the weed varies from crop to crop. Fast growing crops and taller crops are more competitive and will have higher competition coefficients than slow growing and/or shorter ones. Again, increasing the population density of the crop also increases its competitive ability (Doll, 1994).

The major management methods employed in the study area for the purple nutsedge include mechanical control (use of tillage implements) and the use of herbicides (Table 22). Mechanical control both reduces shoot population and increases mortality of tubers by exposing them to desiccation. It may however, break the dormancy of individual tuber buds and tuber chains as well. The net contribution of mechanical control then may be an initial reduction of shoot and tuber population probably followed by an increase in shoot population, depending on conditions available, which may result in an increased tuber population over time if nothing is done to prevent it.

Herbicides used for the control of purple nutsedge have varying control efficiencies and effective periods. Integrated weed management, such as the combination of tillage and systemic herbicides, however ensures effective control for a longer period of time.

The conceptual model

Chronologically, the agroecosystem in which the purple nutsedge occurs begins with the preparation of land at the start of the cropping season

(Figure 15): the land may have been left unused for some time. This is shown in stage 1 of the conceptual model, where the purple nutsedge may be growing together with other weeds, with a load of tubers in soil. Stage 2 illustrates land preparation. For most vegetable crops, some amount of tillage, either by ploughing or hoeing is necessary before planting. Tillage practices result in breaking of dormancy and the rearrangement of the tuber distribution in the soil.

The next stage (3) refers to the point where the vegetable crop is sown either by seed or seedling transplanting. This may occur immediately after stage 2. The life cycles of both the purple nutsedge and the crop begin at this point. The purple nutsedge tuber gives off rhizomes which produce the basal bulb and then the shoot in the next stage whereas the crop seeds also germinate (or takes, in the case of transplanted crops).

In stage 4 therefore, the two plants grow together. The purple nutsedge prominently increases its population (not so much of height) while the crop also increases in weight and height (not in population). Competition between and within the two species begins sometime after the onset of this stage and continues through until some form of weed control (e.g. hoeing) is imposed on the purple nutsedge. It is also the point where major husbandry practices, like fertilizer application, are carried out.

The final stage (5) marks the point where the purple nutsedge flowers and rapid tuber production begins. The crop may mature along with the flowering of the weed or later, depending on its time to maturity. Maturity of the crop may also occur before the flowering of the weed, in which case, the rapid tuber population growth will not occur within the crop's growing cycle.

The growing cycle ends (generally) when the crop finally matures and is harvested. By this moment, the purple nutsedge may have well increased its tuber population and this adds up to the tuber load for the next cropping cycle. The conceptual model is shown in Figure 15.

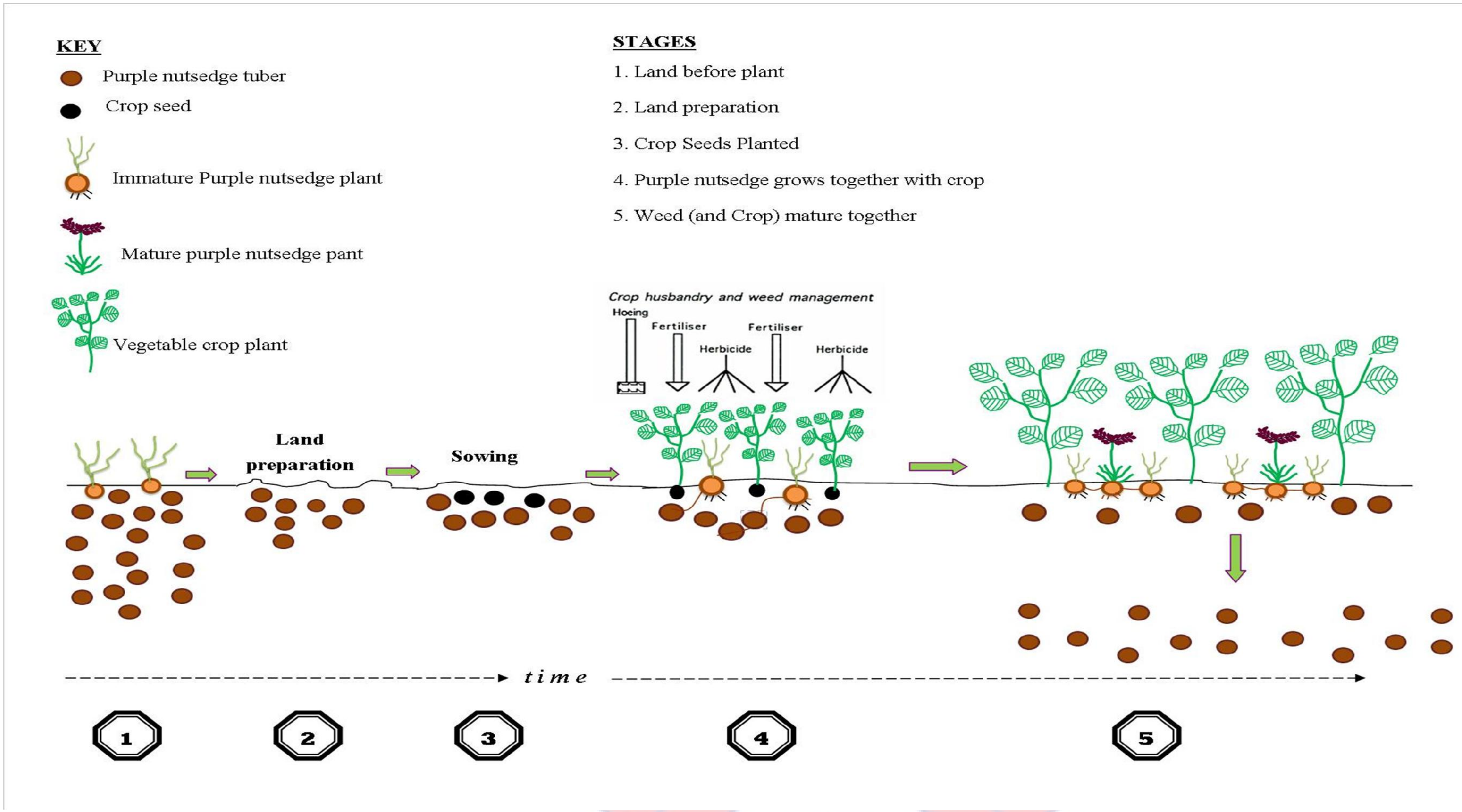


Figure 15: Life cycle of the purple nutsedge –vegetable association (modified from Cousens and Mortimer (1993))

Defining Levels of Complexity for the Model

Models never attain the complexity of the real system and one of the most important choices to be made regards the way the detail in which various aspects of the system are mathematically represented in the model (Brak, 2009). This model therefore looks phenomenologically at the rate of population increase of the purple nutsedge in the vegetable agroecosystem (of southern Ghana) as affected by competition (with the crop), soil moisture, level of light intensity and weed management practices. Other agro ecosystem factors such as other management practices, and pests and diseases are assumed to have negligible effects on the dynamics of the weed. It also looks at the effect of the weed population on yield of the crop.

Processes in the model occur within specified time resolutions and hence, ought to be linked in a specified time-scale. In order not to lose information relative to time differences, it is important to specify the time scale over which the model is developed. This model generally uses weekly time step with daily time step as the smallest time-scale. This implies that what whatever happens over time-scales smaller than the daily time-scale is considered insignificant to the model.

Models also consider the space over which it is developed. They may assume spatial homogeneity or heterogeneity. Model complexity increases with the consideration of spatial heterogeneity. Two assumptions are here made to simplify the model. The first is that ignoring the spatial distribution (aggregated, randomness or evenness) of the weed has negligible effect on the model. Again, that the immigration and emigration processes of the weed are negligible and hence ignoring them does not adversely affect the model.

Random events are part of every natural system and are worth considering in the development of models. They occur in three forms: demographic stochasticity, extrinsic or environmental stochasticity and measurement or sampling error. Models can either be deterministic, stochastic or partly deterministic and partly stochastic. Stochastic models are preferred to deterministic models when the project requires the estimation of variability of the system (small populations involved) or the time to extinction or eradication. The study does not have any of the above as its major objective and hence, the default position of this model was not to include stochasticity unless it became very necessary.

Mathematical Formulation

Intrinsic population dynamics and impact of external factors

The life cycle of the weed begins after land preparation and may immediately be followed by planting. This marks the initial point for the population growth ($t = 0$).

Let N_t = Population of viable tubers (total tuber population – (number of dead tubers + number of dormant tubers)) per m^2 (at 15cm depth) at any time, t.

P_t = Population of weed shoots per m^2 at any time, t

Then N_0 = the variable denoting the initial population of viable tubers.

P_0 = initial number of weed shoots ($P_0 = 0$ due to the land clearing and preparation)

P_1 = number of shoots emerged one week after planting at ($t = 1$)

f = sprouting rate (number of shoots produced per tuber within the first week)

Then, the initial number of shoots produced within the first week, (P_1)

$$P_1 = f \times N_0 \qquad 1$$

(assuming full sunlight and optimum soil moisture level)

However, sprouting of the tubers is significantly affected by amount of soil moisture and light intensity (or shade). To model these, we introduce the two non-interacting parameters, θ and γ which describe the impact of soil moisture and light intensity on sprouting respectively.

$$P_1 = f.\theta.N_0 - (\gamma.S) \qquad 2$$

(considering the effect of shade and soil moisture)

If a pre-emergent weed control measure (e.g. pre-emergent herbicide) is applied before sprouting to kill the tubers, we again introduce the parameter β_0, which describes the proportion of tubers that survive the control measure, then

$$P_1 = f.\theta.N_0.\beta_0 - (\gamma.S) \qquad 3$$

Subsequently, the shoot population increases exponentially (for the period when intra-specific competition is negligible). Thus, the shoot population at any time t is given by,

$$P_t = P_1.e^{kt} \qquad 4$$

where k is the intrinsic rate of population growth,

(assuming negligible intra and inter specific competition and no control measure imposed)

Then

$$\frac{dP_t}{dt} = kP_1e^{kt} \quad 5$$

Substituting 4 into 5,

$$\frac{dP_t}{dt} = kP_t \quad 6$$

This continues until resources become limited and growth turns to be density dependent, resulting in intra-specific competition. At this point, the population levels off into equilibrium, attaining a logistic shape. Thus we multiply k by the expression,

$$1 - \frac{P_t}{K} \quad (K = carrying\ capacity)$$

as suggested by Gillman (2009) which levels off equation 6 into equilibrium as P_t approaches K, to give

$$\frac{dP_t}{dt} = kP_t\left(1 - \frac{P_t}{K}\right) = \frac{kP_t(K-P_t)}{K} \quad 7$$

As weed population increases and the crops grow, interspecific competition between the two species begins. Then

$$\frac{dP_t}{dt} = \frac{kP_t(K-P_t-\alpha_{wc}C)}{K} \quad 8$$

where α_{wc} = competition coefficient of crop on weed and

C = the crop population density

(This describes the Lotka-Volterra competition model)

The effect of weed control imposed at any time, t subsequent to the land preparation is introduced into the model by a parameter $\boldsymbol{\beta_t}$ which describes the reduced rate of weed population growth, $\boldsymbol{k}$.

$$\frac{dP_t}{dt} = \frac{(\beta_t)kP_t(K-P_t-\alpha_{wc}C)}{K} \qquad 9$$

In order to find the weed population at any time (in weeks), we resolve equation 9 by the method of separation of variables and with the aid of partial fractions to give (see Appendix III)

$$P_t = \frac{\Phi}{(1 + Ae^{-r\beta t})^{\Phi/k}} \qquad 10$$

Where

$$\Phi = K - \alpha_{wc}C \qquad 11$$

and

$$A = \frac{\Phi - P_1}{P_1} \qquad 12$$

Effect of weed population on crop yield

Let `Y_0 = Yield of an isolated crop (no competition)

Y_i = Yield of crop infested with i number of weeds per m^2

Y_L = percentage yield loss due to competition with the purple nutsedge,

$$Y_L = \frac{(Y_0 - Y_i)}{Y_0} \times 100 \qquad 13$$

Yield losses increases with increasing weed population densities until weed levels are reached where no significant increase in losses are observed (Radosevich et al., 2007). This suggests an asymptotic exponential relationship between the weed density and yield loss.

$$Y_L = a - be^{-c\times(Pt)} \qquad 14$$

Where a, b and c are parameters fitted by non-linear regression

Long term behaviour of weed population

The number of tubers at the end of the first cropping season, N_f, is given by

$$N_f = N_0 (1+\psi)\alpha \beta \qquad 15$$

Where ψ = the mean number of tubers produced per primary tuber under the prevailing conditions

α = competition coefficient of crops on tuber population

β = the proportion of tubers which survive any control measure imposed

The finite rate of population change, λ, of the tubers is therefore given by

$$\lambda = \frac{N_f}{N_0} = \alpha\beta(1+\psi) \qquad 16$$

If the same practices and conditions continue for i cropping seasons without any fallow periods, then the expected number of tubers at the end of ith season (which by implication equals the N_0 for the $(i+1)$th season) is given by

$$N_i = \lambda^i N_0 \quad \mathbf{17}$$

Discussion

In the strive for simplicity, yet demanding the essential details of the system, the model developed, considers two out of the five stages of development of the purple nutsedge described by Stoller and Sweet (1987): the tubers, which are the primary propagating materials as well as the main underground structures; and the aerial shoots, which comprise the above ground component of the weed. This is an improvement over the single-staged model of the same weed developed by Neeser, Agüero, and Swanton (1998). The other stages (rhizomes, basal bulbs and seeds) do not contribute much to the population changes of the weed and hence were considered not significant in the model.

Similar to most other models of weed population dynamics reviewed by Holst, Rasmussen, and Bastiaans (2007), the formulated model first examines the intrinsic life history of the weed and uses the simple logistic population growth model as its foundation and extends it by incorporating external factors (environmental and agronomic practices) significant to the dynamics. It incorporates two major environmental factors significant to the sprouting of the tubers: soil moisture and shading, and further includes the competitive effect of the vegetable crop and the impact of weed control measures imposed. These afore-mentioned processes were considered the key processes which determine the dynamics of the weed population.

The combination of equations 1 to 3 can be used to determine the number of shoots expected one week after land preparation, whereas equation 4 can be used to determine small, non-competing purple nutsedge population at any time in pure stands. On highly infested fields, however, a combination of equations 10 to 12 can be used to predict the weed population considering the competitive effect of the crop, and weed management measures employed while equations 13 and 14 predicts the yield loss as a result of the purple nutsedge infestation. The long term behaviour of the weed is described by equations 15 to 17 and these can as well be used to determine the period to extinction, should a farmer decide to eradicate the weed from his field.

The various parameters used in the model may differ in their behaviour. First the sprouting rate ($\boldsymbol{f}$), the coefficients of the impact of moisture and light on sprouting ($\boldsymbol{\theta}$ and γ), the intrinsic rate of population change ($\boldsymbol{r}$) and the carrying capacity ($\boldsymbol{K}$) may be affected by ecotypic variations in the weed and factors other than those considered in the model. Again, the competition coefficient of crop on the weed ($\boldsymbol{\alpha_{wc}}$) varies with the vegetable crop planted and may be complicated in mixed cropping systems, where the different crops exert different competitive effects on the weed. It can also affected by the presence of other weeds that affect the growth of both the crop and the purple nutsedge. Ignoring variations due the ecotypes and other sources discussed above, $\boldsymbol{\Phi}$ is considered a constant specific to the various vegetable crops planted at specific densities since $\boldsymbol{K}$ and $\boldsymbol{\alpha_{wc}}$ are both constants. It defines the maximum purple nutsedge population (per m^2) possible for a specific vegetable crop planted at a specific density of C.

In a bid to simplify the model, some limitations were realized: first, the model does not consider that spatial distribution (aggregated, random or even) of the weed on the field. Again the model does not account for effect of tillage practices, such as ploughing, employed under different conditions which either could lead to an increase or decrease in population depending on prevailing conditions.

Conclusion

The population dynamics of the purple nutsedge in a vegetable field has been described theoretically by the model proposed in this study. The various parameters can be determined with the aid of field surveys and/or controlled experiments and then the model can be used to determine appropriate effective and environmentally friendly management measures for the purple nutsedge.

CHAPTER SEVEN

MODEL PARAMETERIZATION, SIMULATION AND UTILIZATION

General Introduction

Parameters refer to those variables in the system model that characterize the state of the system but do not change over time (Nix, 1994). They are very important because they determine the output of the model and hence errors in quantifying them can result in wrong outputs from the model. Their determination is therefore very key to model building

Determination of parameters may be carried out with secondary or simulated data, or data generated from experiments. Since the data needed for this work, with respect to the study area was inadequate, a series of experiments were carried out to determine the parameters. This chapter presents these experiments and then looks at how the parameters were fitted into the model and simulated using R statistical package as a simulation platform. The parameters estimated here included the intrinsic population change parameters and the intraspecific and interspecific competition coefficients.

Experiment 1: Determination of the Density-Dependent Sprouting Rate and the Carrying Capacity of *C. rotundus* in Southern Ghana

Introduction

Sprouting rate refers to the number of shoots produced per tuber in a given time. Unlike many other plants where each seed (or propagative material) produces only one shoot, the many buds on each tuber of the purple nutsedge make it possible for each tuber to produce more than one shoot. Dormancy, a characteristic feature of purple nutsedge tubers, on the other hand, may result in lowered mean number of shoots produced per tuber. These two phenomena (ability to produce multiple shoots and dormancy) greatly affects the population dynamics of purple nutsedge. For many organisms, however, higher density of propagative materials results in lowered birth rate due to intra-specific competition for limited resources. It was unclear whether sprouting rate in purple nutsedge is density dependent or not, hence the experiment.

Carrying capacity refers to the maximum population of an organism that can be sustained by a unit area of its habitat, considering intra-specific competition for resources. It may also be viewed as the population density beyond which no significant increase in population occurs. To determine the carrying capacity for purple nutsedge, it was necessary to compare the sprouting rate of varying tuber densities of the weed in order to find the equilibrium population density.

The purpose of this experiment was therefore to determine the sprouting rate with respect to increasing tuber density and the carrying capacity of purple nutsedge.

Materials and Methods

The study was carried out at the Technology Village of UCC, Ghana, (see Chapter 3 for details) from 25th May to 25th August 2015. Fresh viable tubers of purple nutsedge obtained from the Teaching and Research Farm of the University were planted in plastic pots of 11.3cm diameter filled with loam soil. The tubers were planted at 5cm depth with six planting densities: 1, 8, 32, 64, 128, and 240 tubers per pot corresponding to approximately 25, 200, 800, 1600, 3200, and 6000 tubers per m^2 respectively. The experiment was laid out with Completely Randomized Design with six replications, on a concrete platform with no shading.

Data was collected on the number of shoots and tubers in each pot and sprouting rate was calculated as:

$$\textit{Sprouting rate} = \frac{\textit{number of shoots}}{\textit{number of tubers}} \qquad \mathbf{18}$$

The carrying capacity was determined as the equilibrium population beyond which no significant population increase was observed. The data collected was plotted on an XY chart (sprouting rate against number of tubers) and analyzed with non-linear regression.

Results and Discussion

Sprouting rate

Purple nutsedge sprouting rate figures ranged between 0.5 and 2.8 shoots per tuber and was observed to be dependent on tuber density. Higher figures were associated with lower densities and vice versa. The result suggested a negative exponential relationship between tuber density and sprouting rate with the sprouting rate decreasing drastically with increasing tuber density up to 50 tubers per pot and then levelling off into equilibrium. The negative exponential model was fitted to the data, and this gave the equation:

$$\textit{Sprouting rate} = 0.90 + 3.17\exp(-0.05 \times \textit{tuber density}) \quad \textbf{19}$$

with all parameters being significant (p<0.01) (Figure 16).

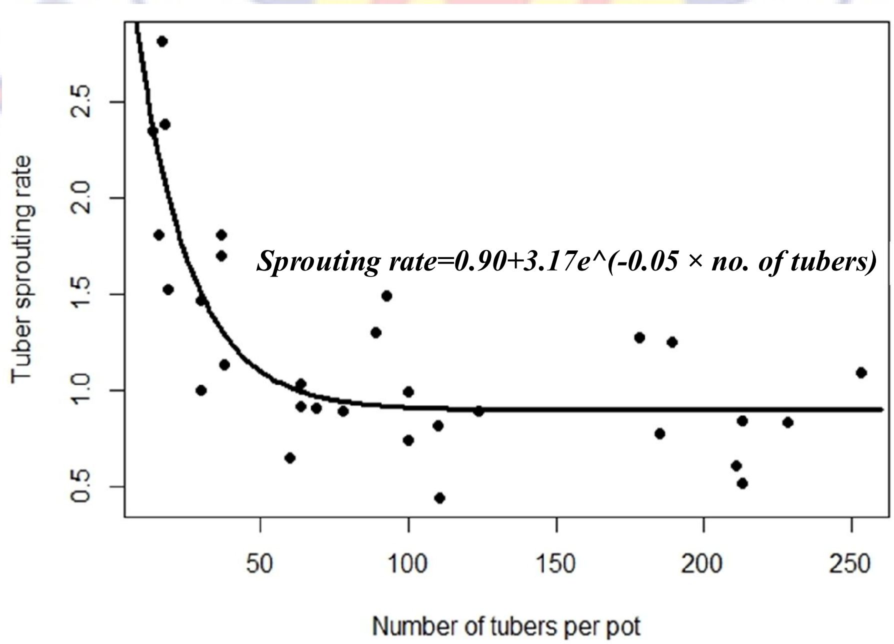


Figure 16: Density-dependent sprouting rate of purple nutsedge tubers

The reduction in sprouting rate with increasing tuber density is consistent with the result of the work by Lati, Filin, and Eizenberg (2012) which pointed to a reduced shoot biomass produced per tuber with 10 tubers per pot, compared to the one tuber per pot. This may be as result of intra-specific competition for limited resources such as soil moisture and/or light as a result of crowding. The result also suggests that at lower tuber densities, dormancy is probably lowered as tubers are compelled to sprout at higher rates, possibly in a bid to ensure survival and improve competitive ability in the ecosystem by increased photosynthesis. However, this may provide a window for eradication since a higher percentage of viable buds are forced to sprout and hence, if removed, sprouting in the next generation could be minimal.

Carrying Capacity

The number of shoots per pot increased with increasing number tubers per pot up to 64 tubers per pot where the rate of increase reduced, and levelled off after approximately 150 tubers per pot (Figure 17). The carrying capacity was found to be 141.2 ± 1.28 ($p<0.001$) which corresponds to approximately 1364 per m^2.

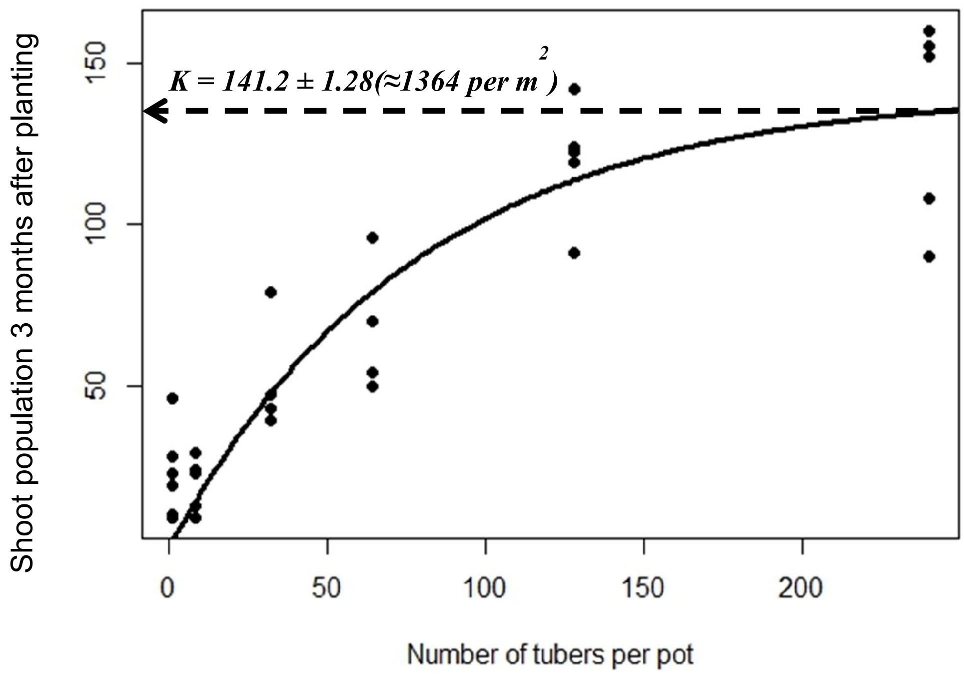


Figure 17: Carrying capacity (*K*) of purple nutsedge determined from the maximum shoot population per pot (after 3 months)

The result is in line with the assertion by Horowitz (1972b) that in monocultures of the purple nutsedge, the weed grows to a population of approximately 10 million to 30 million stands per ha (1000 to 3000 per m^2). Beyond this point, population growth remains in an equilibrium; that is, rate of increase is balanced by mortality rate. The carrying population can be affected by environmental factors such as soil moisture, nutrient levels, and light since it is directly influenced by intra-specific competition for those resources and hence the determination of this figure assumed adequate quantities of these resources.

Conclusion

The study gave a negative exponential relationship between the tuber density and sprouting rate and the carrying capacity of the purple nutsedge tubers as approximately 1364 tubers per m^2 assuming adequate quantities of resources.

Experiment 2: Effect of Shading on Sprouting in *Cyperus rotundus*

Introduction

Sprouting of purple nutsedge viable tubers in the tropics is heavily dependent on some environmental factors, especially, light intensity (or shading) and soil moisture (Stoller & Sweet, 1987). Shading reportedly reduces sprouting in purple nutsedge considerably and this has been attributed to the weed's C_4 photosynthetic pathway which demands much light for proliferation. This effect of shading can be exploited in the management of the weed (Doll, 1994) by employing any appropriate means of reducing the amount of light that reaches the soil surface, especially after land preparation and before planting. Thus the extent to which shading affects the weed will be much necessary in any model of population dynamics of this weed. This experiment thus sought to quantify the effect of shading on the sprouting of the purple nutsedge.

Soil moisture, though very important, was not factored because it could not be exploited in the control of the weed since it was not practicable to deny the weed of moisture while ensuring adequate supply of moisture to the crop while they remain on the same piece of land.

Materials and Methods

The experiment was conducted at the Technology village of the School of Agriculture, of UCC (see Chapter 3 for details) in plastics pots of diameter 13cm filled with loamy soil. Viable tubers obtained from the Teaching and Research Farm of the same institution were planted in the pots at a density of approximately 23 per m^2 (three tubers per pot) and the required treatments imposed.

A total of five shading levels, 0%, 25%, 50%, 75%, 100% shading, were imposed in the experiment which was replicated five times and laid out in Completely Randomized Design. The treatments were imposed by covering the pots with black polythene mulch with holes cut out to the required percentage. The 0% treatment was not covered with the mulch.

The pots were monitored for days to first sprouting and cumulative number of sprouts. Data collected were subjected to appropriate regression analysis.

Results and discussion

Shading was found to have a linear relationship with sprouting, with a gradient of -0.46, which by definition, is the coefficient of the effect of shading on sprouting (Table 41).

Table 41: GLM with the log-link function on the effect of shading on weed shoot population

	Estimate	Std. Error	z value	P-value
Intercept	9.9	0.62	19.180	0.00031***
Shading	-0.46	0.05	-9.959	0.00215 ***

*** Parameter estimate is significant at 0.001 level

The result confirms the finding by Patterson (1982) and Santos et al. (1997a) that shading drastically reduces sprouting in purple nutsedge and showed that use of black polythene mulch could effectively reduce sprouting in purple nutsedge.

Experiment 3: Determination of parameters of intrinsic population dynamics and the inter-specific competition coefficient of cabbage on purple nutsedge population

Introduction

In mixed plant stands, as pertains to typical agro-ecosystems, interspecific competition occurs between the crops and the weeds on the field. This affects both the growth of the weeds and the performance of the crops. The effect of competition of one species on the other is designated as interspecific competition coefficient, denoted by, α_{12}, representing the effect of species 2 on species 1 and vice versa. The coefficient is given by the first derivative of the regression curve describing the relationship between species 2 (independent variable) and species 1 (dependent variable).

To evaluate the effect of the crop on the weed, it is important to compare the population growth of the weed under different cropping densities to a monoculture of the weed. The monoculture also helps to determine the intrinsic population growth parameters for the weed.

For the purpose of this work, cabbage (*Brassica oleracea* var. capitata) was used as the test crop, to evaluate its competitive effect on purple nutsedge.

The crop was chosen because of its enormous nutritional and economic importance in the study area, and the serious impact of purple nutsedge on this vegetable crop.

This experiment was thus conducted to determine the parameters of intrinsic population growth of the weed, and the competition coefficient of cabbage on purple nutsedge.

Materials and Methods

Study area

The study was carried out at the Teaching and Research Farm of the School of Agriculture, UCC and repeated at the Demonstration field of the Department of Horticulture of KNUST (see Chapter 3 for details), on fields that were heavily and relatively uniformly infested with the purple nutsedge.

Field layout and experimental design

The experiments were conducted using additive designs (Radosevich et al., 2007) where the density of the crop was varied on the relatively uniform purple nutsedge infested field. The variety of cabbage used was the oxylus. Seeds of this variety were sown in the nursery on the 7th July, 2015 and pricked out after 10 days at the Teaching and Research Farm of the School of Agriculture, UCC. The experimental fields was first ploughed and harrowed and then laid out and divided into experimental plots as required. Treatments for the experiments consisted of a monoculture of the purple nutsedge, which was meant to evaluate the parameters of intrinsic population dynamics of the weed, and varying cabbage planting densities. Planting densities of 16, 4, 2, and 1 cabbage stands per m^2 were imposed by planting 25 plants per plot with 0.25m, 0.5m, 0.75m, 1.0m spacing respectively, with the square planting pattern. The plots were separated at 2m apart from each other and laid out with the randomized complete block design with six replications. The seedlings were transplanted on the 18th August 2015 and all cultural practices (except weed control) were carried out as required. For weed control, all other weeds, except the purple nutsedge, were removed by hand picking.

Data collection and analyses

Data was collected on growth and yield of cabbage and the shoot and tuber populations of purple nutsedge. Specifically, the growth parameters measured were plant height, number of unfurled leaves, length of largest leaf, width of largest leaf (W) and Leaf area (LA). Yield parameters measured were head diameter, head height, root weight, untrimmed head weight, and trimmed head weight. The number of shoots per unit area was taken with the aid of a 25cm × 25cm quadrat. The number of purple nutsedge tubers per m^2 was taken at a depth of 10cm. The data collected were subjected to appropriate regression analysis.

Results

The shoot population on the purple nutsedge monoculture plots grew exponentially until the fifth week, after which the rate of growth decreased probably due to the onset of intraspecific competition. The intrinsic rate of growth (k) was thus estimated with the data for the first five weeks.

Intrinsic rate of population growth

The shoot population grew exponentially from about 12 in the first week to approximately 70 by the fifth week. The exponential model was fitted to the data and this gave the relationship as:

$$\textbf{Shoot population} = \mathit{5.73\ exp\ (0.49 \times time)} \qquad \textbf{20}$$

Comparing equations 20 and 4 (page 135), k is estimated as 0.49 (Figure 18).

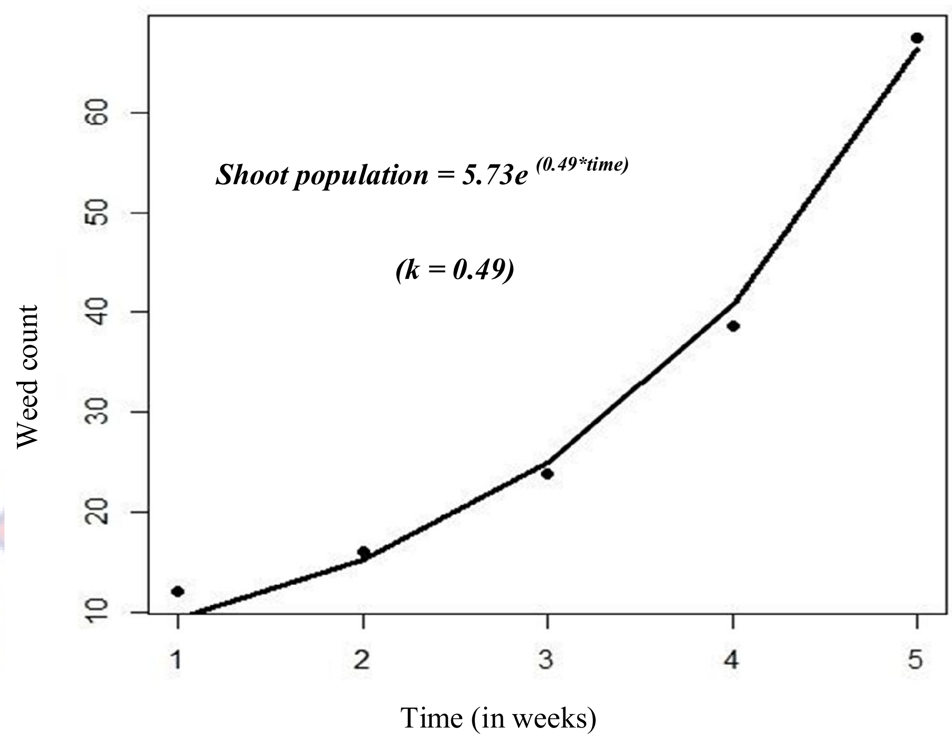


Figure 18: Exponential growth of weed population before onset of intraspecific competition

Intraspecific competition

The onset of the intraspecific competition after the fifth week reduced the rate of population growth. This reduction was to continue until the carrying capacity was reached. The three-parameter logistic model (Crawley, 2007) was thus fitted to the data (Figure 19).

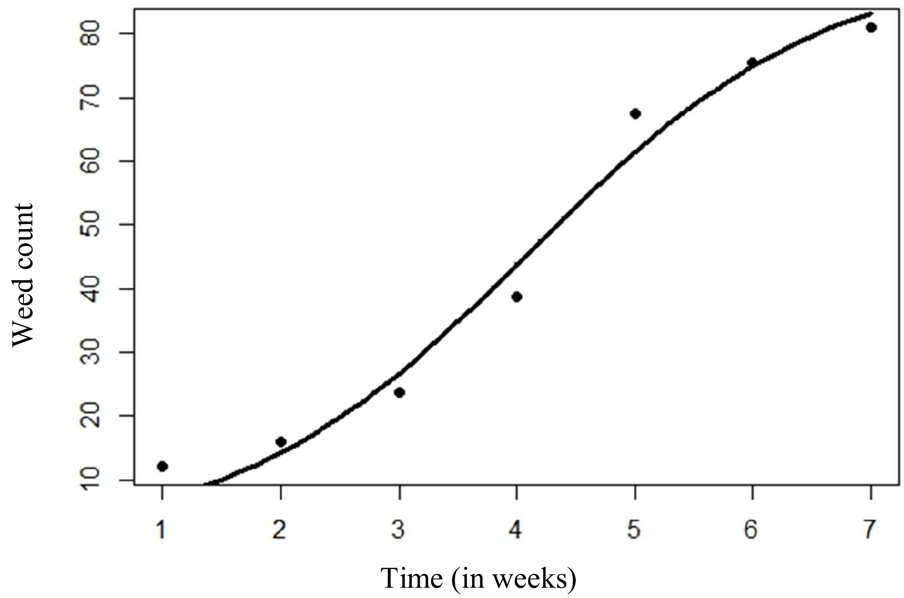


Figure 19: Logistic growth of weed shoot population after onset of intraspecific competition

Interspecific competition coefficient

Intercrop spacing was observed to have a linear relationship with weed density. The data was subjected to analysis with the Generalized Linear Model (with the poisson family) and this gave the coefficient of the interspecific competition as 1.95 ± 0.29. (Table 42)

Table 42: GLM with the log-link function on the effect of intercrop spacing on weed shoot population

	Estimate	Std. Error	z value	P-value
Intercept	2.4706	0.2342	10.551	< 2e-16 ***
Crop spacing	1.9533	0.2895	6.748	1.5e-11 ***

*** Parameter estimate is significant at 0.001 level.

Intra-specific competition in cabbage

As crop spacing reduces, competition within the individual crop plants arises and this results in reduced growth and yield. Table 43 shows the analysis of the intra-specific competition in the cabbage as the crop spacing reduced and indicates a sharp decline (gradient) in growth and yield parameters with decreasing crop spacing.

Table 43: SLR on the effect intra-specific competition on some growth and yield parameters of cabbage

Growth Parameter	Intercept ± standard error	Gradient ± standard error	Adjusted R^2	P-Value (for gradient)
Plant height	20.02** ± 1.74	12.13 ± 2.30	0.48	<0.01
Length of largest leaf	18.23** ± 1.94	14.38 ± 2.57	0.51	<0.01
Width of Largest leaf	12.32** ± 1.80	20.68 ± 2.38	0.72	<0.01
Number of unfurled leaves	9.72** ± 0.92	3.91 ± 1.22	0.24	<0.01
Total Plant Weight	-0.78^{NS} ± 0.48	5.42 ± 0.52	0.78	<0.01
Root weight	1.574^{NS} ± 7.45	92.89 ± 9.845	0.75	<0.01
Untrimmed head weight	-0.80* ± 0.38	5.01 ± 0.50	0.77	<0.01
Trimmed head weight	0.71* ± 0.29	3.55 ± 0.39	0.74	<0.01
Head height	17.60* ± 7.93	110.61±10.47	0.79	<0.01
Head width	-3.54^{NS} ± 48.29	117.44±63.78	0.19	<0.01

NS Parameter estimate **not** significant at 0.05 level
* Parameter estimate Significant at 0.05 level
** Parameter estimate Significant at 0.01 level

Discussion

The population growth of purple nutsedge in pure stand initially followed the exponential growth and subsequently the logistic growth patterns. This is typical of population growth of organisms since resources available to them reduce with time as the population increases and results in intraspecific competition. The rate of population growth was found to be quiet high and this depicts the characteristic strategy of the weed to quickly increase its population in order to out-compete other plant in its vicinity.

The GLM on the interspecific competitive effect of cabbage on the purple nutsedge gave an intercept of 2.4706 ± 0.2342, implying that if the intercrop spacing should reduce to 0, this number (the intercept) will still occur. This shows first, the competitive ability of the weed and then, the inability of the cabbage to totally eliminate the weed considering it competitive effect. The gradient of 1.9533 ± 0.2895 may as well not be so large to cause so much reduction in the population of the weed.

Within the cabbage, intra-specific competition was very severe, with the yield parameters being more affected than the growth parameter. The most reduced parameters were the untrimmed head weight, total plant weight, trimmed head weight and the root weight in that order. The negative intercept of the untrimmed head weight indicates that crop will fail to head if planted at a spacing equal to or below the point of the regression line where the untrimmed head weight is equal to zero.

The results from this experiment has shown that the competition within individual cabbage plants is more severe than the effect of the cabbage on the purple nutsedge and hence care must be taken in any attempt to smother purple nutsedge with cabbage.

Conclusion

The population growth of the purple nutsedge in pure stand initially followed a rapid exponential growth and subsequently the logistic population growth pattern. Inter-specific competitive effect of cabbage on purple nutsedge was found to be on the lower side with intra-specific competition within the cabbage rather on the higher side, with high detrimental effects on its yield parameters more than growth.

Experiment 4: Impact of weed population on crop yield

Introduction

The purpose of weed management is to reduce competition from the weed to the barest minimum and improve the yield of the crop. Thus any recommended strategy for the management of the weed should ultimately result in improved yield of the crop. It is therefore important for the model to predict the expected crop yield loss (or gain) with respect to the weed population. The relationship between the weed population and crop yield is thus of importance in this study.

According to Radosevich et al. (2007), crop yield usually decreases with increasing weed densities to a point, beyond which further increases in weed density do not significantly reduce crop yield. This experiment was therefore aimed at estimating the relationship between weed population and yield loss in the test crop (cabbage).

Materials and Methods

The experiment was as well conducted at the Teaching and Research Farms of the School of Agriculture, UCC. and repeated the at Demonstration Fields of the Department of Horticulture, KNUST (see Chapter 3 for details) from 14th August 2015 to 28th October 2015. This experiment was also laid out with the additive design proposed by Radosevich et al. (2007) similar to the one described previously (experiment 3). However, the population density for the cabbage was rather kept constant whiles the weed population density was varied. The cabbage was planted at a spacing of 60cm x 60cm (farmers' practice) on 3m x 3m plots with varying densities of the purple nutsedge. In total, the experiment comprised 35 individual plots arranged in seven rows by five columns and spaced 2m apart (Figure 20). Agronomic practices and data collection were the same as for the previous experiment (experiment 3). Data collected was analysed by appropriate correlation and regression analysis.

Figure 20: Plate of field experiment at the teaching and research farm

Results

Increased weed populations generally reduce yield of crops. However the most severe damage is caused to the crop during the critical competition period, which for cabbage, occurs between three to five weeks, after planting (Alan & Herbert, 1991; Weaver, 1984). The relationship between weed population and yield was thus determined with the weed density after five weeks.

A number of equations describing the relationship between weed population and yield loss have been proposed (Cousens & Mortimer, 1995), but the relationship between the two in this experiment was found to follow the negative exponential curve. Hence the two-parameter negative exponential model,

$$Y = A \times \exp(-B \times \text{weed density}) \qquad 21$$

where Y is the response variable, and A and B are parameters fitted by regression,

was fitted to the data for the various growth and yield parameters measured (Tables 44 and 45).

Table 44: Effect of purple nutsedge density on some growth parameters of cabbage

Growth Parameter	A ± standard error	B ± standard error	P-Value
Plant height	33.15 ± 0.73	0.005 ± 0.001	<0.01
Width of Largest leaf	34.19 ± 1.07	0.008 ± 0.02	<0.01
Length of largest leaf	36.17 ± 0.89	0.008 ± 0.001	<0.01
Number of unfurled leaves	13.21 ± 0.43	0.004 ± 0.001	<0.01
Leaf Area	29.98 ± 0.41	-0.10 ± 0.02	<0.01

Table 45: Effect purple nutsedge density on some yield parameters of cabbage

Yield Parameter	A ± standard error	B ± standard error	P-Value
Total Plant Weight	5.75 ± 0.32	0.03 ± 0.004	<0.01
Root weight	123.20 ± 7.88	0.02 ± 0.004	<0.01
Trimmed head weight	3.39 ± 0.26	0.05 ± 0.006	<0.01
Head height	137.7 ± 4.13	0.010 ± 0.001	<0.01
Head width	157.4 ± 5.77	0.048 ± 0.002	<0.01

For the purpose of the model, yield loss as a result of the purple nutsedge infestation was estimated with the untrimmed head weight since that constituted the final produce of cabbage that is sold at the farm gate. The yield of an isolated crop (no competition from purple nutsedge) was first estimated and this was used to calculate the mean percentage yield loss for various plots in the experiment.

The yield (untrimmed head weight) of an isolated cabbage was found to be 5.93kg. With increasing weed density, the yield reduced consistently until reaching a constant beyond which increasing weed density did not result in further decrease in yield. The relationship was given as

$$\textit{Yield} = 1.23 + 4.70\exp(-0.017 \times \textit{weed density}) \qquad \textbf{22}$$

The result is presented in Figure 21

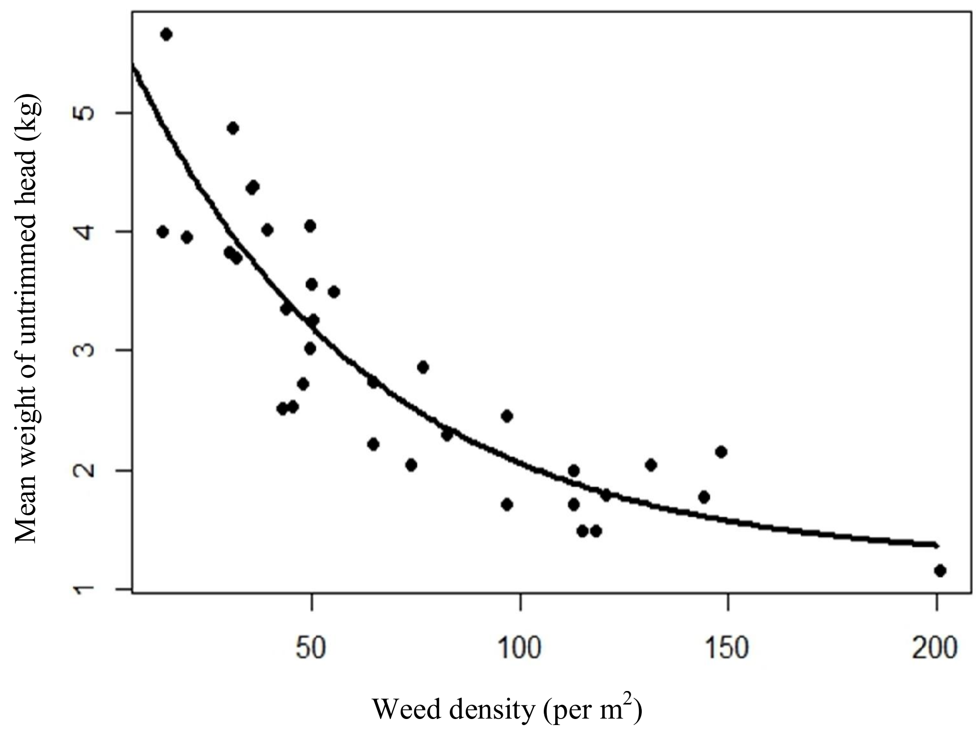


Figure 21: Effect of purple nutsedge density on weight of untrimmed head

The relationship between weed population and percentage yield loss was derived using the asymptotic exponential curve. It was given as:

Percentage yield loss = 79.26(1-exp (-0.02*Weed density)) **23**

The result gives the maximum yield loss due to purple nutsedge infestation as 79.26% (Figure 22).

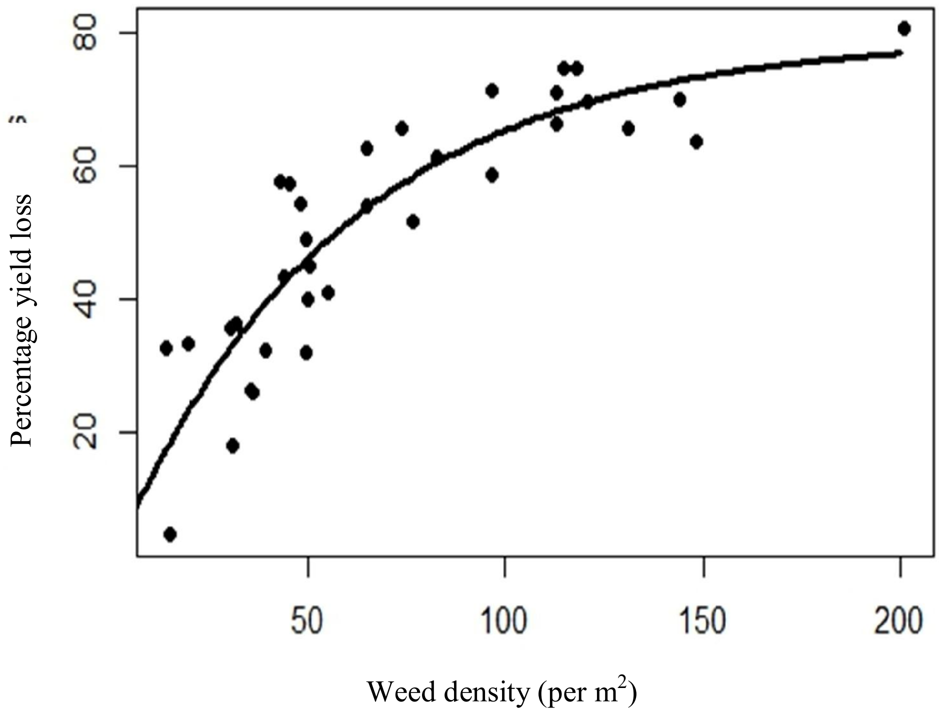


Figure 22: Relationship between weed density and percentage yield loss

Correlation between the various parameters measured showed a significant negative correlation ($p < 0.05$) between weed count and all growth and yield parameters indicating that the weed adversely affects both growth and yield of the crop, with untrimmed head weight, trimmed head weight and total plant weight being among the most reduced parameters (Table 46).

Table 46: Correlations between purple nutsedge density, and growth and yield parameters of cabbage

	Weed Density	Plant height	Width of Largest leaf	Length of largest leaf	Total plant fresh weight	Root fresh weight	Trimmed Head weight	Untrimmed head weight	Height of head	Width of Head	Number leaves
Weed Density	1										
Plant height	-.646**	1									
Width of Largest leaf	-.663**	.708**	1								
Length of largest leaf	-.719**	.794**	.920**	1							
Total plant fresh weight	-.847**	.731**	.666**	.765**	1						
Root fresh weight	-.725**	.618**	.709**	.764**	.859**	1					
Trimmed Head weight	-.757**	.690**	.612**	.661**	.900**	.803**	1				
Untrimmed head weight	-.828**	.721**	.669**	.716**	.928**	.757**	.898**	1			
Height of head	-.742**	.695**	.668**	.728**	.784**	.596**	.713**	.804**	1		
Width of Head	-.776**	.700**	.538**	.636**	.870**	.656**	.815**	.895**	.864**	1	
Number leaves	.435**	-.444**	-.689**	-.684**	-.349*	-.471**	-0.239	-0.311	-.394*	-0.24	1

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Discussion

The results from the experiment clearly indicates that purple nutsedge adversely affects growth and yield parameters of cabbage measured with yield parameters being more affected than the growth parameters. This confirms earlier findings on the effect of the weed on vegetable crops (William & Warren, 1975). The maximum yield reduction (in terms of untrimmed head weight) was found to be 79.26 per cent, higher than the 35 per cent reported by William and Warren (1975). The difference could be as a result of varietal differences in the cabbage and/or ecotypic variations in the purple nutsedge. Differences due to environments (experimental sites) could also have contributed to the difference in percentage losses. The high maximum percentage yield loss may be due to the fact that cabbage, being a green leafy vegetable, requires more nitrogen for growth and especially, yield, whereas the purple nutsedge remains a heavy feeder of nitrogen. Thus the weed deprives the crop of its most important nutrient, nitrogen.

Conclusion

Purple nutsedge significantly reduced both growth and yield of cabbage up to a maximum of 79.26% of untrimmed head weight. The reduction followed the negative exponential curve for all parameters measured.

Model Simulation

Introduction

After determination of parameters for the conceptual model, the various parameters will then have to be fitted back and tested. Due to complex nature of the calculations involved, models are usually simulated with a simulation platform. A number of such platforms are available but for the purpose of this work the statistical software, R, was used for the simulation. This is because R is a very comprehensive statistical analysis package that incorporates all the standard statistical tests, models, and analyses, and as well, provides a comprehensive language for managing and manipulating data

Variables Determined for the Model

Table 47 summarizes the state variables and parameters derived from the various experiments.

Table 47: Summary of state variable and constants derived for the Model

Parameter	Notation	Estimated Mean Value or function	Standard Error of Estimate
Initial number of tubers per m^2	N_0	State variable	-
Sprouting rate (per tuber)	f	$0.90+3.17e(-0.05\times N_0)$	
		0.90***	0.09
		3.17***	1.09
		0.05***	0.02
Tuber survival rate	β_0	State variable	-
Coefficient of the effect of shading	γ	0.46***	0.05
Coefficient of the effect of soil moisture	θ		
Percentage shading	S	State variable	
Initial shoot population	P_0	$\beta_0.N_0.f.s\text{-}(\gamma.S)$	
Intrinsic rate of population increase	k	0.49	0.03
Time (in weeks)	t	State variable	
Shoot Population at any given time	P_t	Model output	
Carrying capacity	K	≈ 1364 per m^2	
Competition coefficient of crop on weed	α_{wc}	1.95	0.28
Cropping density	C	State variable	
Proportion of population surviving weed management	B_t	State variable	
Yield of an isolated crop	Y_0	5.93kg per plant	
Yield loss	Y_L	Model output	

NS Parameter estimate **not** significant at 0.05 level
* Parameter estimate Significant at 0.05 level
** Parameter estimate Significant at 0.01 level

R Script for model simulation

```
#Defining variables for model
N=?#intial tuber density per m^2
f=0.90+3.17*exp(-0.05*N)#fecundity
j=?#survival rate
S=?#percentage shading
s=0.46#coefficient of shading
P0= (N*f*j)-s*S#initial population density
K=1364#carrying capacity
a=1.95#interspecific competition coefficient of cabbage on weed
t=?#time (in weeks)
r=0.49#intrinsic rate of population change
C=?#intercropping spacing
b=?#proportion of weeds surviving a control measure
E=K-(a*C)
A=((E-P0)/P0)^(K/E)
B=A*exp(-r*b*t)
PT=E/(1+B)^(E/K)
Y0=5.93#yield of an isolated crop
Yl=79.08*(1-exp(-0.004*PT))
```

?: State variable (value required)

Testing and Validating the Model

Introduction

Ecological models are expected to represent the reality in order to help solve identified problems. However, for various reasons, they may not accurately give correct representations, and hence ought to be checked to ascertain how well they achieve the purpose for which they are built. This phase of model building is often described as model verification and validation.

Verifying and validating a model begins with checks on the conceptual framework of the model: if the conceptual framework is wrong, outputs from the models can in no way be right, and ends with comparing model predictions with reality. It is as well expedient to check whether the model equations make sense, test the model's internal logic and ascertain the correctness of the model solution (Soetaert & Herman, 2009). In ecological modelling, verification differs from validation although the two are often confused and thought to have the same meaning. Rykiel (1996) distinguished the two terms: he defined verification as the demonstration that the modelling formalism is correct and validation as a demonstration that a model, within its domain of applicability, possesses a satisfactory range of accuracy consistent with the intended application of the model. Rykiel explained that validation indicates that the model is acceptable for use and not necessarily that the model embodies the absolute truth. He clarified that operational validation involves a comparison of simulated data with data obtained by observation and measurement of the real system. In effect, while verification examines the modelling formalism, validation examines model output vis-à-vis the real system.

It was necessary to ensure that the model that has been developed was meaningful and useful for the purpose for which it was developed, hence the objective of this section was to verify and validate the model to ensure its credibility.

Materials and Methods

The model was evaluated to ascertain its credibility in two major steps: the first step was to examine the conceptual validity of the model, whereas the second involved statistical comparison between simulated outputs of the model and observed field data.

The conceptual validity was verified by examining the theories and assumptions underlying the conceptual framework, the conceptual framework's representation of the real system, the internal logic of the model, the mathematical formulation and causal relationships of the model as suggested by Rykiel (1996).

The underlying theories (as derived from existing literature) and assumptions were discussed with colleagues from both modelling and non-modelling backgrounds to identify lapses which could have weighty effects in the conceptual framework of the model. This test, which has been described as the "tell-it-to-a-colleague" test by Soetaert and Herman (2009) was conducted for various stages of the model building process and the results incorporated back into the model.

The conceptual framework's representation of reality was compared to existing literature to ensure accuracy, while the internal logic of the mathematical formulation was tested by asking the general question "does the model behave as expected?", under which various expectations of the model were examined. The questions asked included "does model output fall within expected range?",

The second step involved statistical tests of comparisons between simulated outputs of the model to observed field data as suggested by Mayer and Butler (1993) and Power (1993). The purpose of this step was to assess how well the model represented the real system and to determine if the model could adequately serve the purpose for which it was developed. Data for this step was obtained from a field experiment conducted between January 2016 and March 2016 on a purple nutsedge infested field at the teaching and research farm of UCC. The experimented consisted of 10 experimental plots of the test crop, cabbage (of the same oxylus variety as used in earlier experiments), planted at a spacing of 60cm x 60cm within each plot. The plots were 2.4m x 2.4m in size and contained 16 plants each. They were spaced 2m apart and from each other. All agronomic practices on the field, except weed management, were carried out as required. For weed management, all other weeds, except the purple nutsedge were ridded off by handpicking. Data was collected on the number of tubers per m^2 at the start of the experiment and the population of purple nutsedge shoots on weekly basis. Data was also collected on the growth and yield of the cabbage and the percentage yield loss as well. The data collected was compared to predicted outputs from the model by scatter plots analysed by correlations as used by Neeser et al. (1998)

Results and Discussion

Since the “tell-it-to-a-colleague” test was conducted as part of the model building process, the result from the test was incorporated directly into the model and thus the final model encompassed the test result.

The conceptual framework followed the idealised life-cycle of a weed-crop association proposed by Cousens and Mortimer (1995) and adapted by Mortimer (1994). The assumptions used in the conceptual framework and their justifications are discussed in Chapter six. Despite the fact that some of the assumptions could have weighty effect on the model output, they were necessary to ensure model simplicity and practicability.

A close evaluation of the model using the questions posed indicated that the model behaved reasonably as expected: it did not give negative state variables; predictions at the extreme ends were reasonable and it could as well give back input that did not need to change.

For example, in the absence of viable tubers in the soil,

$N = 0$ and this give $P_t = 0$ for anytime, t.

In the event where all tubers are dormant,

$f = 0$, and this as well gives $P_t = 0$ for anytime t

Again, if we assume an initial shoot population of 100,

That is $P_0 = 100$, the model gives $P_0 = 100$ as expected.

As $N \rightarrow \infty$, P_t, for anytime t, does not exceed the carrying capacity of 1364 per m^2 which is reasonable for the fact that the weed cannot exceed the maximum population that can be supported.

Finally, the maximum percentage yield loss of 79.23% is never exceeded, irrespective of the weed population.

The comparison between the predicted model output and the experimental data showed significant positive correlations ($p < 0.01$) the weed population after one week, three weeks, five weeks and the percentage yield loss. This demonstrates that the model reasonably represents the real system and can serve the purpose for which it was developed. The results are presented in Figures 23 to 26

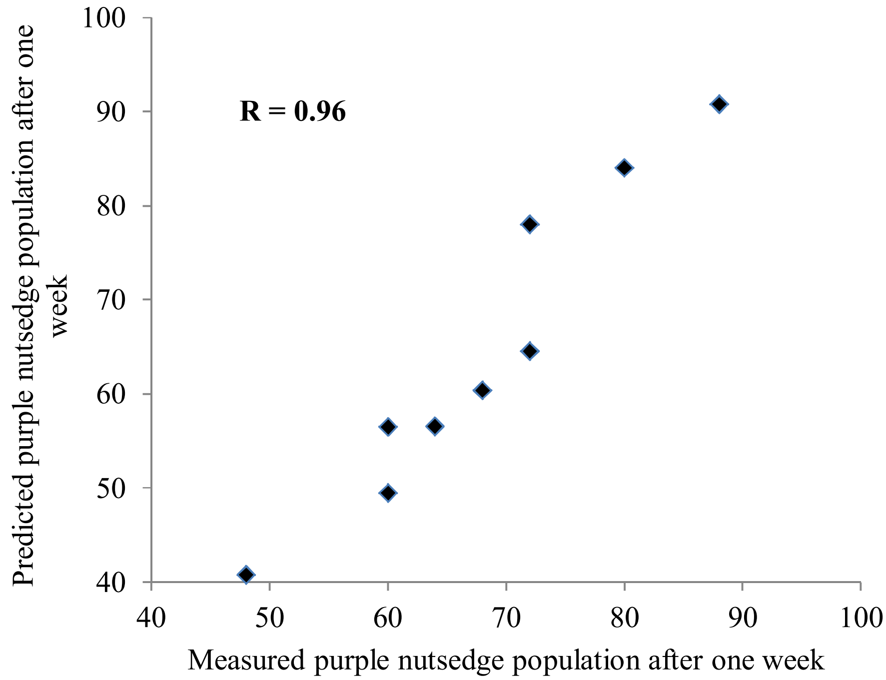


Figure 23: Comparison between measured and predicted purple nutsedge population after one week

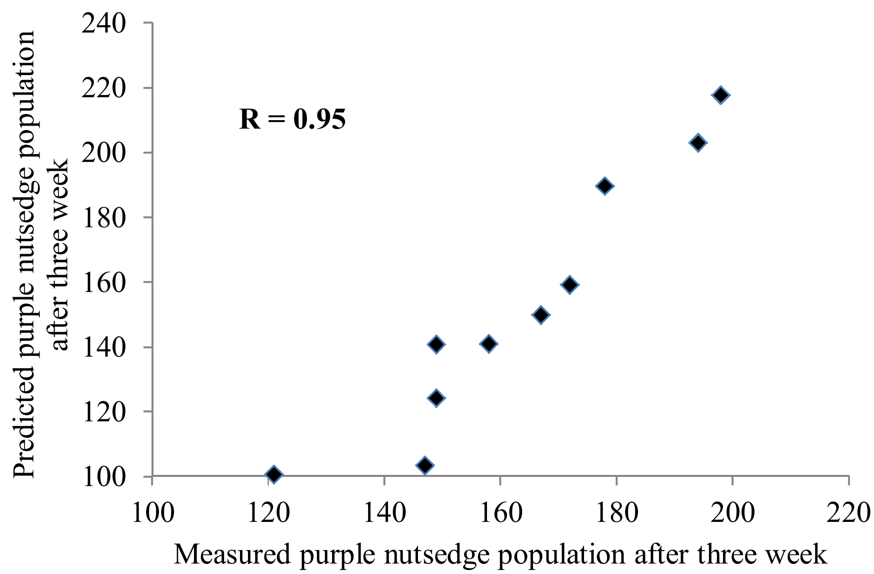


Figure 24: Comparison between measured and predicted purple nutsedge population after three weeks

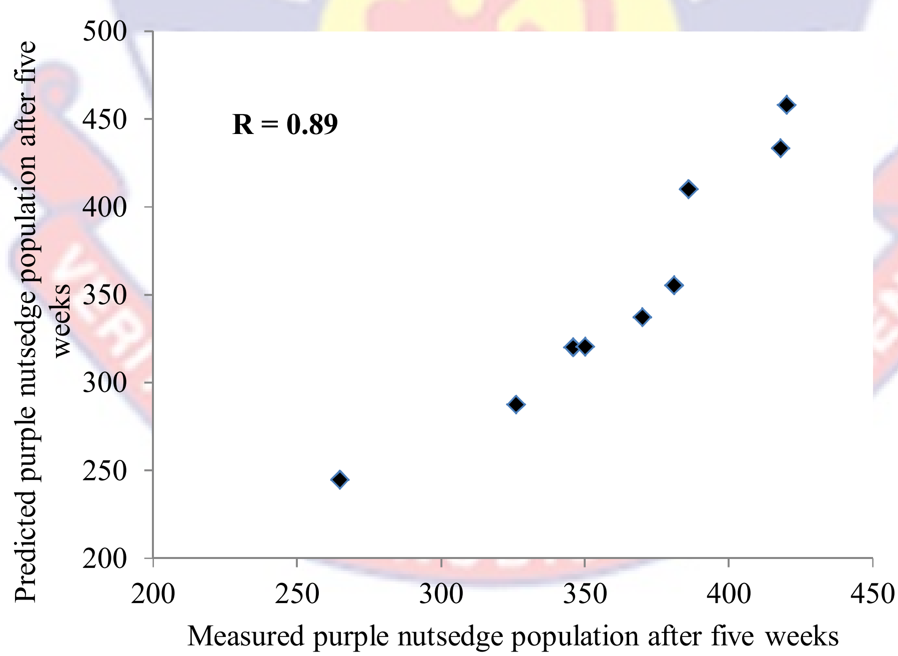


Figure 25: Comparison between measured and predicted purple nutsedge population after five weeks

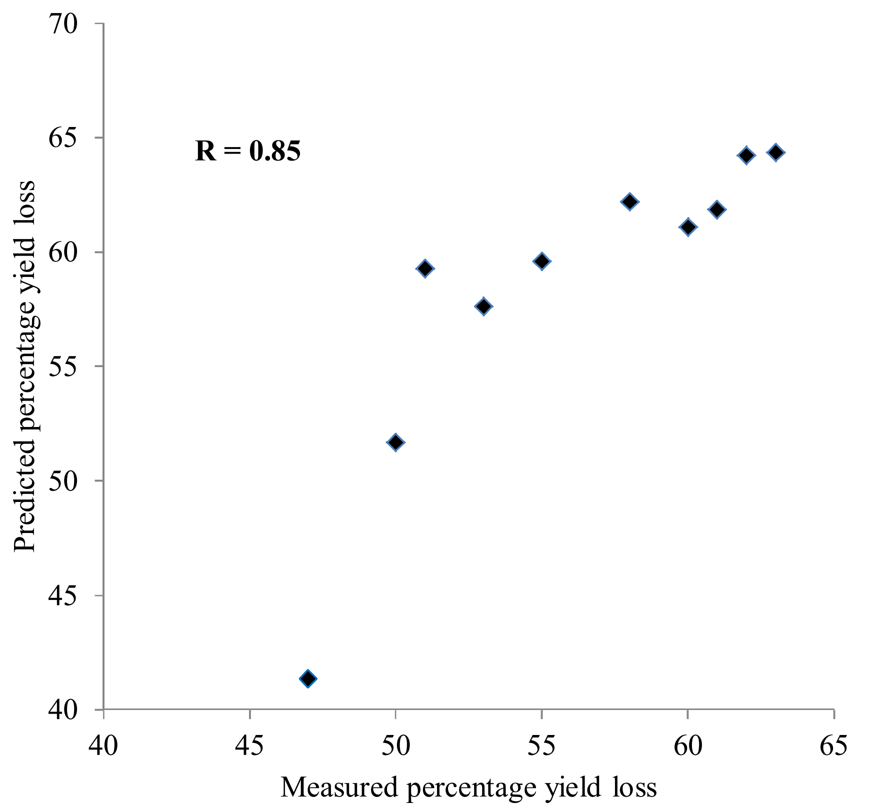


Figure 26: Comparison between measured and predicted percentage yield loss

Conclusion

From the various tests conducted, the model reasonably represents the real system and accurately predicts the various outputs. It is therefore valid and useful for the purpose for which it was built.

Investigating Weed Management Options with the Model (Sensitivity Analysis)

Introduction

Various options remain for the management of weeds in vegetable fields. These span from cultural, mechanical, chemical and biological, among others. Each of these, however, is expected to either kill a certain proportion of the weeds to allow for proper growth of the crop (reduce competition with the crop) or reduce their rate of growth (either physiological or population growth). The timing of the management intervention is also very important in determining its effectiveness.

To obtain an effective management method, a number of state variables in the model can be altered to see their effect on the population of the weed and their ultimate effect on the yield. Some of the variables, however may not have any practical meaning in weed management. The others which could be used in formulation of weed management regimes were hence altered within practical limits to assess their effectiveness in managing the weed and ultimately improving yield.

Effect of initial tuber density on weed population and yield of crop

Initial viable tuber density on a field may range from 0 (where the weed does not occur) to thousands per m^2 (heavily infested fields). Varying the effect of this variable between 10 tubers per m^2 (very low infestation) to 500 tubers per m^2 showed that the weed population could reach between 100 and 1000 shoots per m^2 after five weeks if no control measure was employed.

This would result in between 39% and 80% yield loss. The results are shown in Figure 27

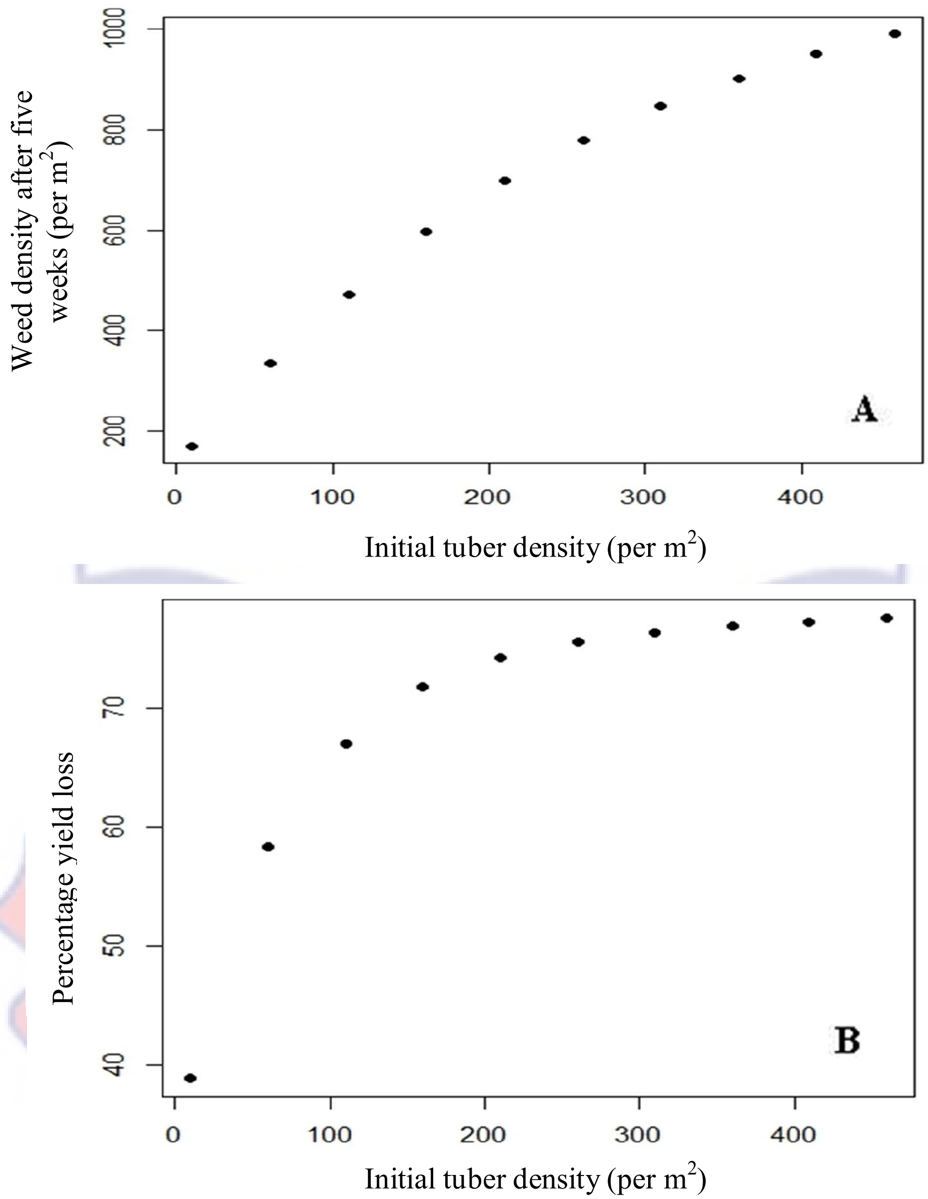


Figure 27: Effect of initial tuber density on shoot population after 5 weeks (A) and percentage yield loss (B)

The idea of reduction of viable tuber density as a means of weed management is vital in site selection for crop production, especially when there are competing sites. It is only wise to select the field with lower tuber density to ensure good yield. The idea could also be employed by manually picking out tubers from small fields where practicable. This however does not guarantee maximum production since reducing the density to as low as 10 tubers per m^2 would still result in about 39% yield loss.

Effect of initial tuber survival rate on weed population and yield of crop

Tuber survival refers to a combination of survival from natural mortality (i.e. the proportion of tubers surviving from death caused by environmental factors such as desiccation in dry periods and predation from natural biological agents) and survival from artificially imposed control measures. The combined effect may range from 0 (where all tubers are killed) to 1 (where none of the viable tubers is killed), though the extreme ends (0 and 1) may never occur. Assuming a field with 200 tubers per m^2 infestation, the model indicates that weed density could remain 0 and ensure maximum crop yield (percentage yield loss = 0) if it was possible to kill all the viable tubers (survival rate = 0), or would reach 800 shoots per m^2 by the fifth week if no control measure was implemented, resulting in about 80% yield loss. The results are shown in Figure 28

A number of measures can be put in before planting to increase tuber mortality rate. These include ploughing in the dry hot period to expose tubers to desiccation, applying systemic pre-emergent herbicide with residual effect on tubers, or introducing a natural enemy to the tubers to increase tuber mortality before planting. Very high mortality rates are however required to achieve meaningful results. Using this approach may demand heavy initial capital investment to ensure the high mortality rate required, otherwise mortality rate of even 60% (0.4 survival rate) would still result in about 60% yield loss (assuming initial tuber infestation rate of 200 per m^2).

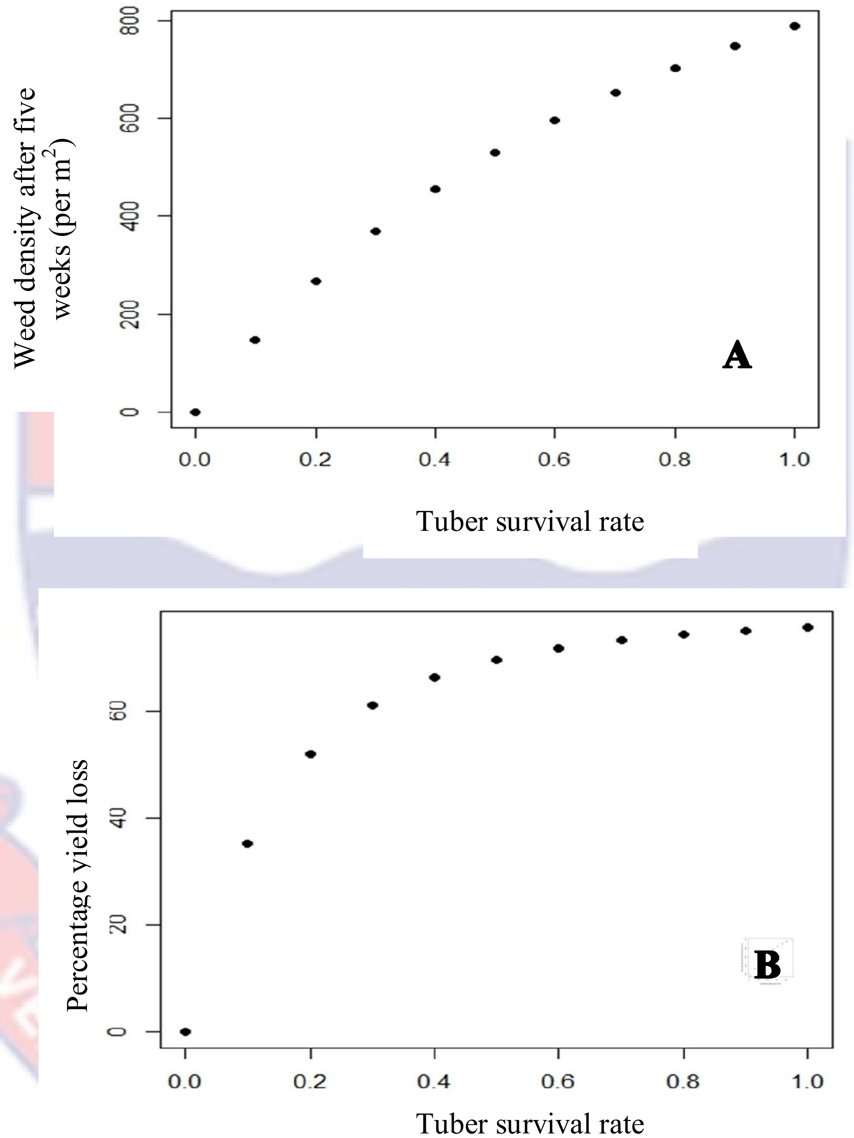


Figure 28: Effect of tuber survival rate on weed density after five weeks (A) and percentage yield loss (B) (assuming 200 tubers per m^2)

Effect of shading on weed population and yield of crop

Shading occurs when the amount or proportion of sunlight reaching the weed is reduced. Since the weed under study is sun-loving, shading is expected to have great effect on it. It is however clear that although shading reduced weed population after 5 weeks, even maximum shading (100%) would not effectively control the weed (assuming initial viable tuber density of 200 tubers per m^2 with 0.75 initial survival rate) (Figure 29). Its subsequent effect on yield was also not encouraging.

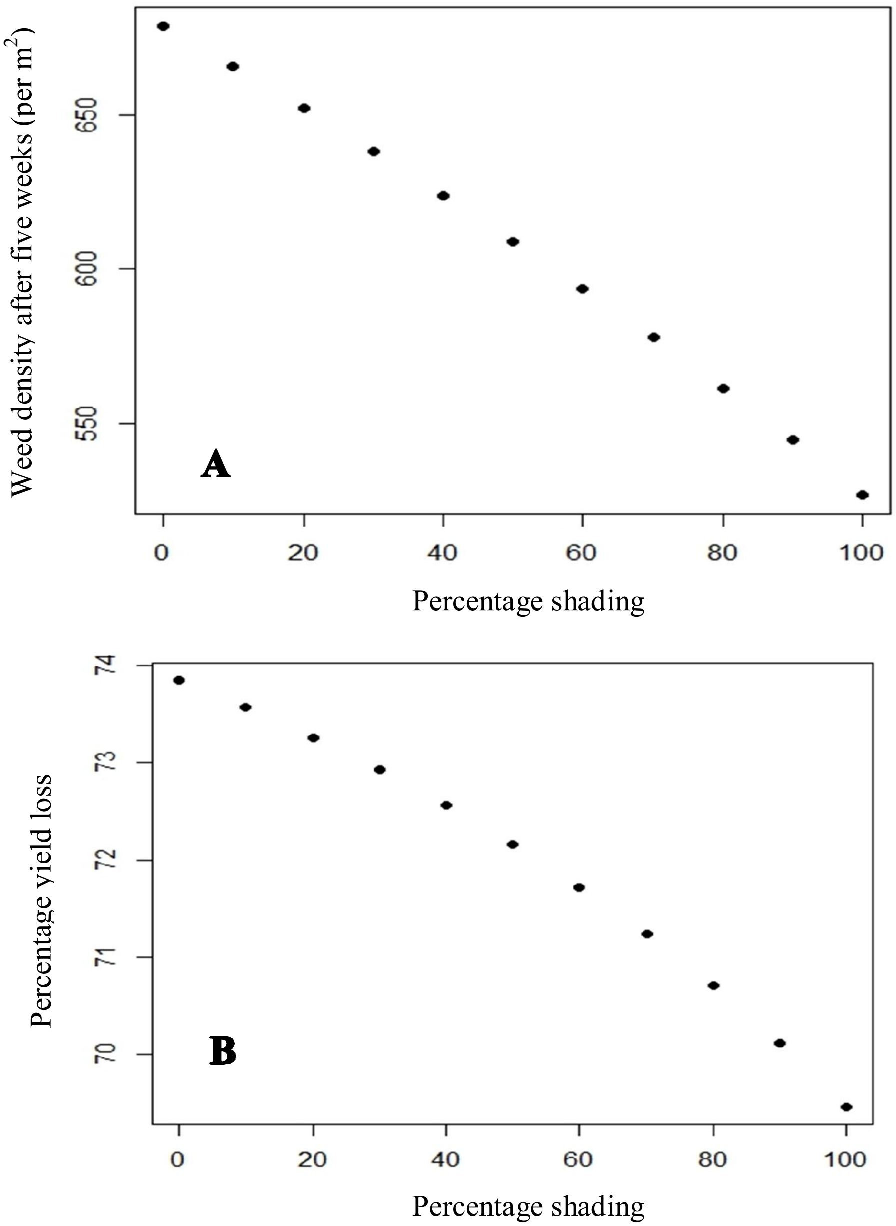


Figure 29: Effect of shading on weed density after five weeks (A) and percentage yield loss (B)

Shading may be employed with the use of mulch (dry leaves, plastic, etc) or by the use of fast growing crops which quickly grow and soon shade the weed. Contrary to suggestions that these could be used effectively, it is clear that mulching alone will not be effective and this is demonstrated by the fact that the weed can grow even under concrete blocks if the area is heavily infested. However, if no other measure remains, shading may still be used to reduce the effect of the weed.

Using inter-crop spacing or planting density to control purple nutsedge

Decreasing inter-crop spacing (increasing planting density) could also be used for weed control (Doll, 1994). In cabbage production, the least practicable spacing may be 40cm within and between rows (Norman, 1992), below which intraspecific competition drastically reduces yield (see Table 42). Thus evaluation was done for intercrop spacing between 0.4m and 1m, assuming initial viable tuber density of 200 tubers per m^2 with 0.75 survival rate. The results showed a decrease in weed population with decreasing intercrop spacing. The reduction was however minimal and did not affect yield (Figure 30).

The idea of using narrower intercrop spacing as a means of suppressing purple nutsedge growth was suggested by Doll (1994) and was based on the fact that the crop would compete better with narrower spacing. However, the rate of population increase of the weed remains higher than the rate of growth of the crop and hence damage is caused to the crop before the 5^{th} week. The cabbage would, by this stage, not have closed its canopy enough to suppress the weed growth and ensure effective control.

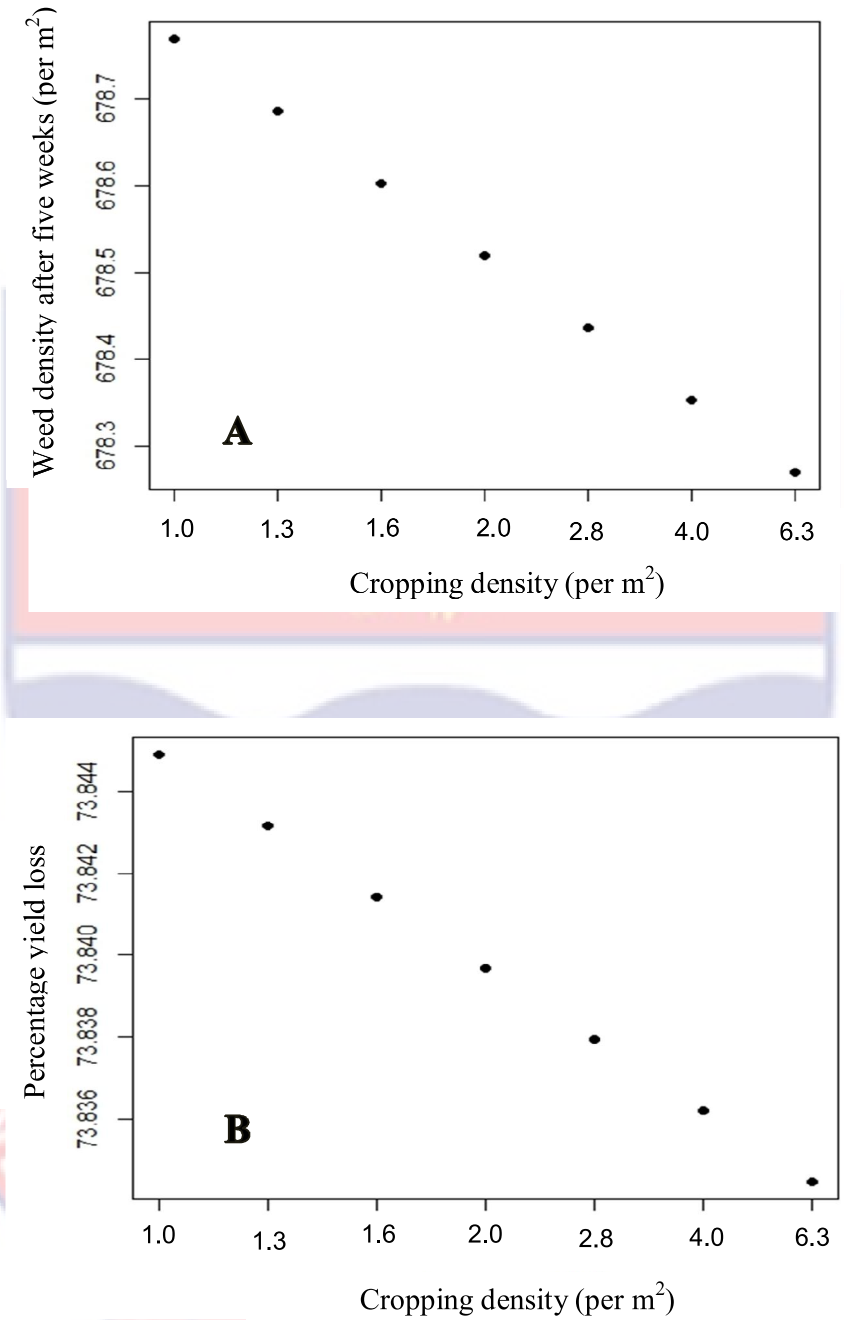


Figure 30:Effect of cropping density on weed density after five weeks (A) and percentage yield loss (B)

Effect of weed management methods imposed after emergence of weed

The common practice in weed management in vegetable fields is to reduce the weed population or growth rate after it emerges. The effectiveness of the method depends on two key things: the proportion of weed killed (or the extent to which the rate of increase is reduced) and the timing of the application. The general practice of most farmers is to weed three weeks after planting to avert yield losses (see Table 11).

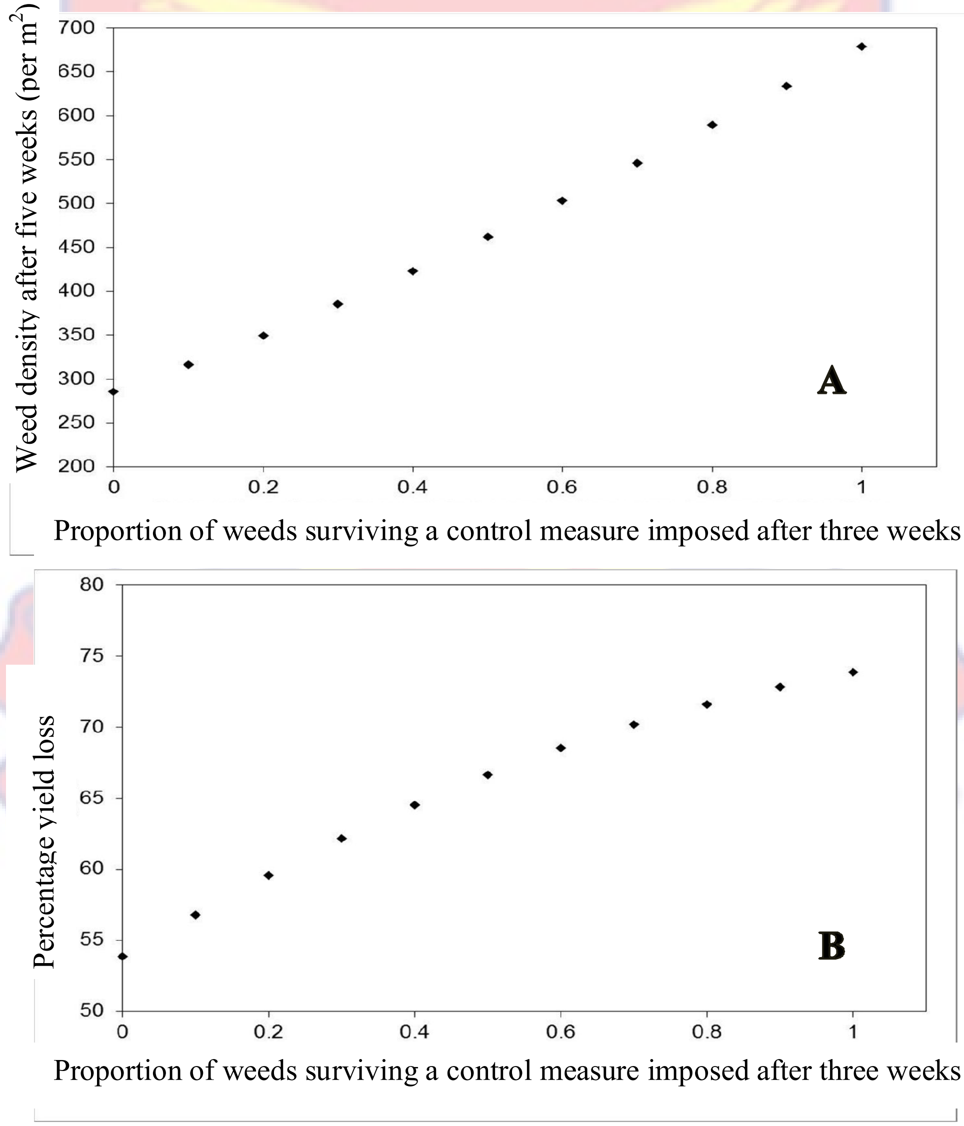
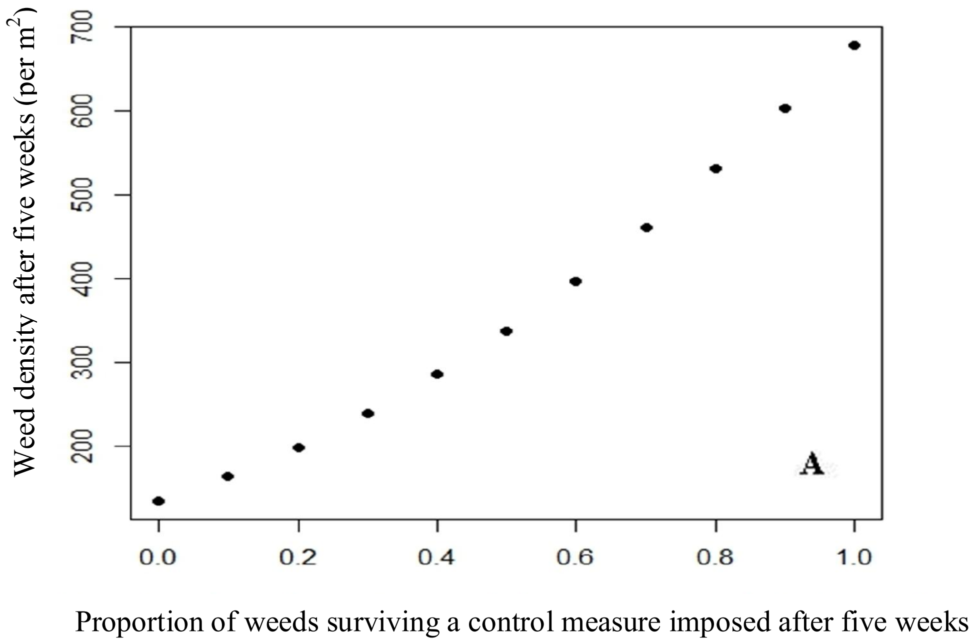


Figure 31: Effect of weed control measure imposed after three weeks on weed density after five weeks (A) and percentage yield loss (B)



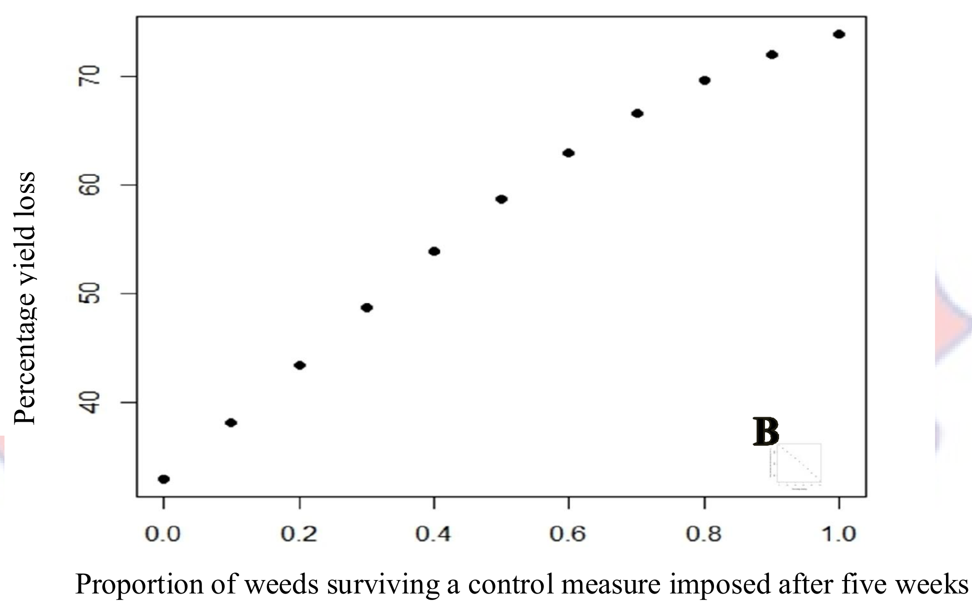


Figure 32: Effect of control measure imposed after five weeks on weed density after five weeks (A) and percentage yield loss (B)

Some other farmers may want to wait for the critical competition period (the 5th week) before putting in a control measure. The effect of varying efficacies of the control measures employed at the two periods are presented in Figures 31 and 32.

It is clear from Figures 31 and 32 that, no matter the efficacy, of the control measure, if it is imposed three or five weeks after planting, heavy losses will still be incurred. This is because the effect of the weed begins after emergence of the weed (peaking in the critical competition period). The best may be to keep the weeds completely off until the critical competition period is over.

The measures that can be employed using this approach include manual weeding and use of herbicides. These control measures come with varying efficacies to control weeds for a period of time. From the analysis, if any of these is able to keep the weed population low till the fifth week, it is likely to improve yield.

Integrated weed management

The above discussion indicates that no single control method will be able to effectively control the weed. However, control measures targeted at reducing initial number of viable tubers seem to be more effective than those targeted at the weed after emergence. This suggests that control methods imposed after weed growth are not likely to be effective. The best control methods will be those targeted at the tubers and imposed before planting. Feasibility and cost may however hinder the use of this approach.

A very important consideration may be to integrate various methods in an integrated weed management programme. Possible combinations from the model include: ensuring low initial tuber density in combination with shading, and adjusting crop spacing to increase competitive effect of crop on the weed. These may be possible where reduction in initial tuber density is practicable, however, for heavily infested fields, a control method targeted at the initial tuber density (such as ploughing during the dry period to expose them to desiccation) may serve the same purpose as selecting a site with low tuber density. This may then be combined with shading, use of competitive effect of the crop, or the employment of another control measure after planting (or weed emergence). Other combinations such as reducing planting spacing (use of competitive effect of crop) and application of a control measure may give non-practicable combinations: the closer the crop spacing, the more difficult it is to apply another control measure.

Combining a reduction in the initial number of tubers (which can be very expensive in situations where the land is already heavily infested, but very effective), and shading (which alone is not effective with heavily infested fields) can give a very effective control (Figure 33).

Integration of reduced of initial viable tuber density with shading

Even though shading alone did not prove effective with the assumed initial viable tuber density of 200 tubers per m^2, it appeared to be effective with lower densities. This indicates an interaction effect between the two methods of control. Figure 33 shows that weed density at week 5 could still remain at approximately 0 if the initial tuber density is reduced to approximately 40 and the field is given 100% shading (for instance mulched with black plastic mulch). The corresponding yield loss is also minimized. However, with increasing initial tuber density, shading loses its efficacy and weed growth sharply increases, resulting in a corresponding increase in yield loss. Integrating these two therefore may only be recommended if initial tuber density can be reduced to approximately 40 tubers per m^2 or less.

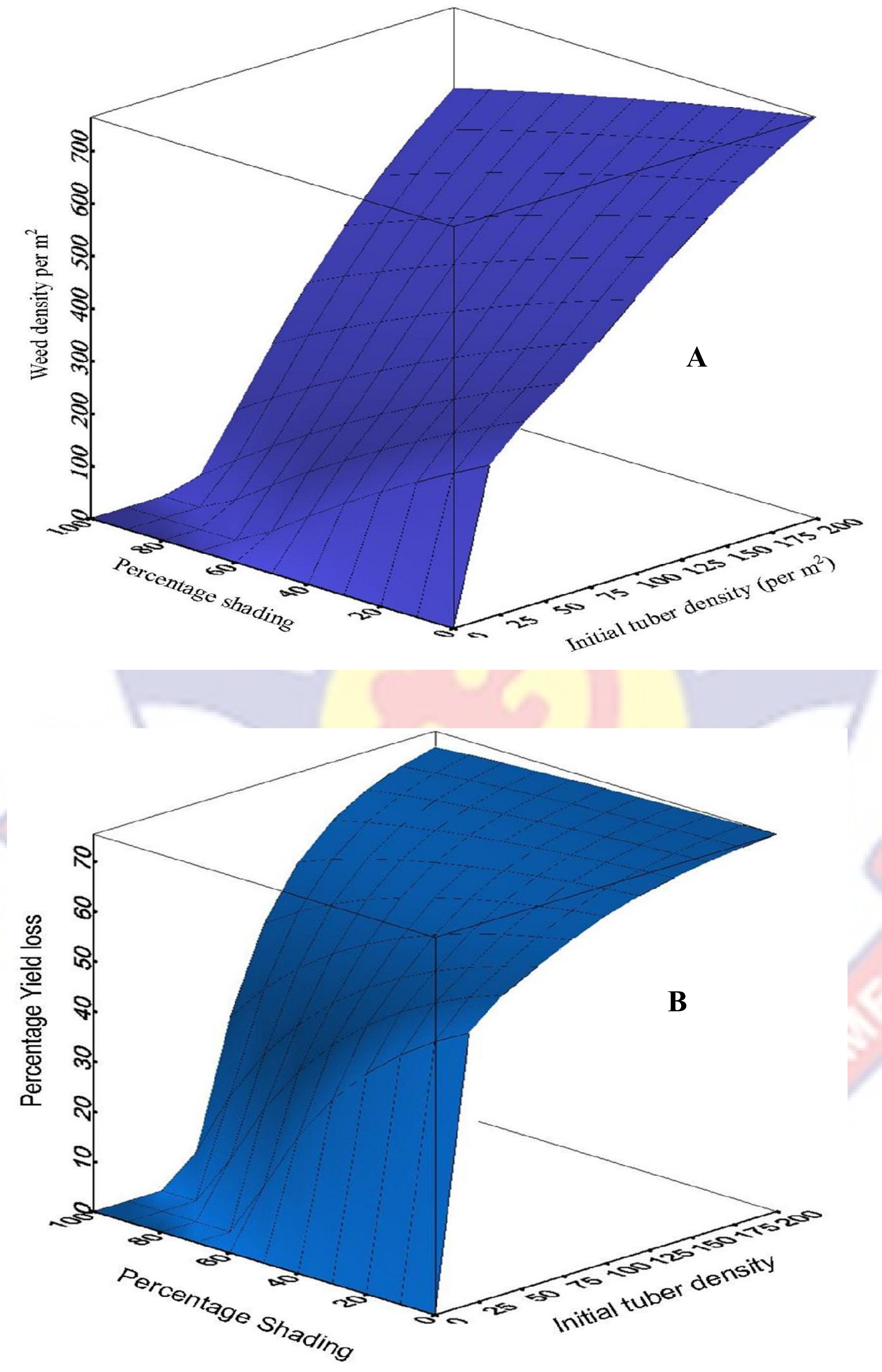


Figure 33: Effect of integrating reduced initial viable tuber density with shading on weed density after 5 weeks (A) and percentage yield loss (B)

Integration of reduced initial viable tuber density with the adjustment of crop row spacing

Similar to shading, adjustment of crop row spacing alone was not effective in reducing the weed population density with the assumed initial viable tuber density of 200 weeds per m^2 (Figure 29). However, it did not show the interaction effect with initial viable tuber density as did the shading. Even though it shows some reduction in weed population at five weeks after weed emergence, and eventually in the percentage yield loss, the reduction was not enough to ensure effective control of the weed. Effective control could only be achieved with zero initial viable tuber density which may not be practically attainable with heavily infested fields. Figure 34 shows this output from the model.

It is again inconsistent with the suggestion by Doll (1994) that adjusting crop row spacing to the narrowest practical level could help in the control of the weed. The approach does not even seem to work when integrated with a reduction in initial viable tuber density. This suggests that the test crop, cabbage, may have a lower competitive effect on the weed with the range of row spacing tested. Perhaps, this may only be for the first few weeks after planting, where the weed grows rapidly whereas the cabbage makes effort to take, hence the weed gains an added advantage and enormously affect the crop. Reducing the row spacing of cabbage further may also be impracticable since this will drastically increase intraspecific competition and reduce yield considerably (Tables 42 and 43).

While this approach would not work for the cabbage, it may work for more competitive crops. For example, the closer row spacing used for lettuce, coupled with its fast growing nature may offer a higher competitive effect on the weed and this may effectively reduce the population of, and eventually the yield loss from the weed (Norman, 1992).

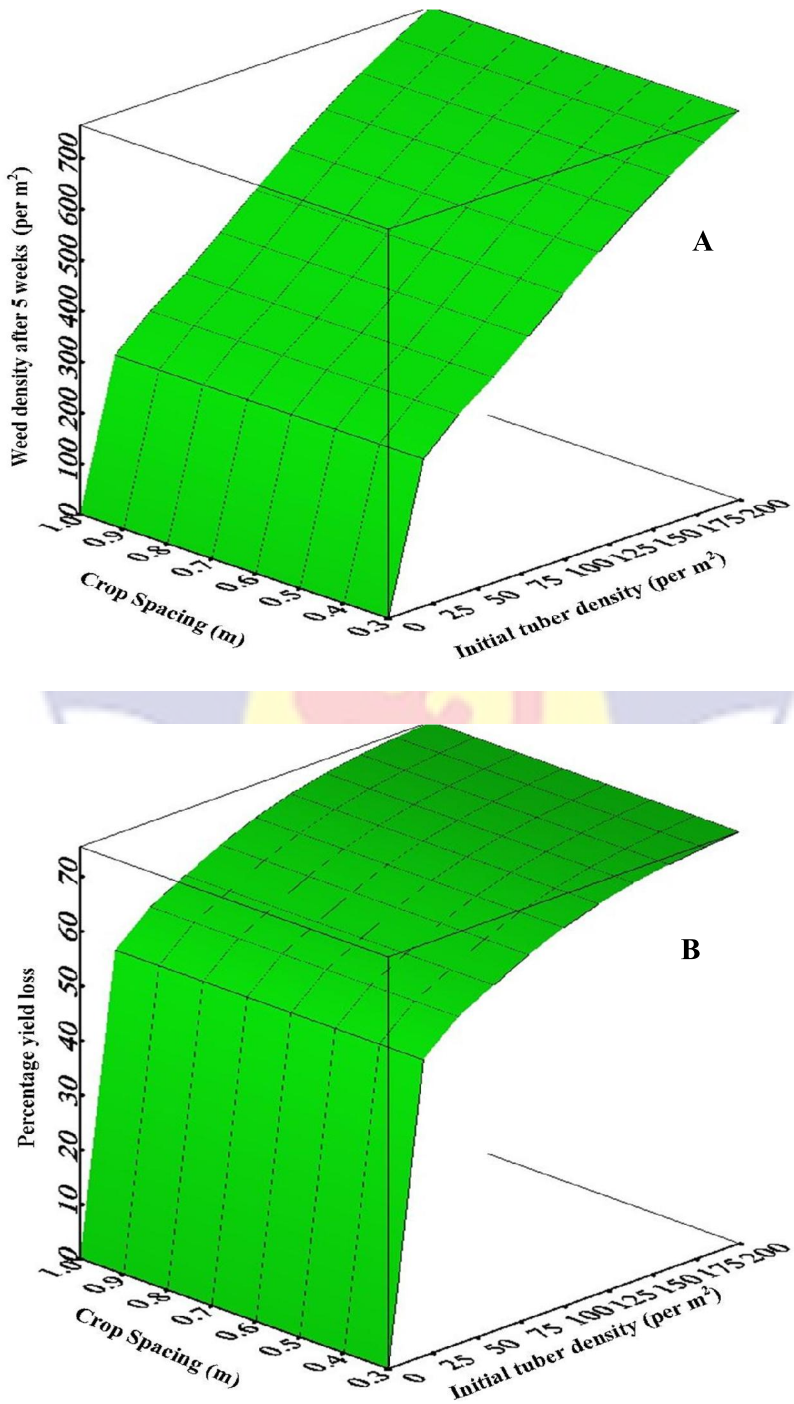


Figure 34: Effect of integrating reduced initial viable tuber density with crop spacing on weed density after 5 weeks (A) and percentage yield loss (B)

Integration of shading with the adjustment of crop row spacing

Figures 29 and 30 indicates that both shading and adjustment of crop row spacing individually could not effectively control the weed. However, shading, together with the reduction of initial viable tuber density was able to control the weed effectively. The model was therefore used to ascertain if integrating shading and adjustment of crop row spacing could also effectively control the weed. The best result from the integration of the two was given by combining 100% shading with the least crop row spacing of 0.3m by 0.3m, but this could only reduce the weed density at 5 weeks after planting to approximately 600 per m^2 which corresponded to approximately 72% yield loss (Figure 35). This obviously does not give a good control of the weed and cannot be used under any circumstances. The reason for the inability of the two methods to put together to control the weed may simply be that the two do not complement each other well enough to provide a good control synergy as there is very low interaction between the two to enhance weed control.

Despite its inability to work with the test crop, it is possible that the approach will work with more competitive crops such as lettuce as discussed earlier.

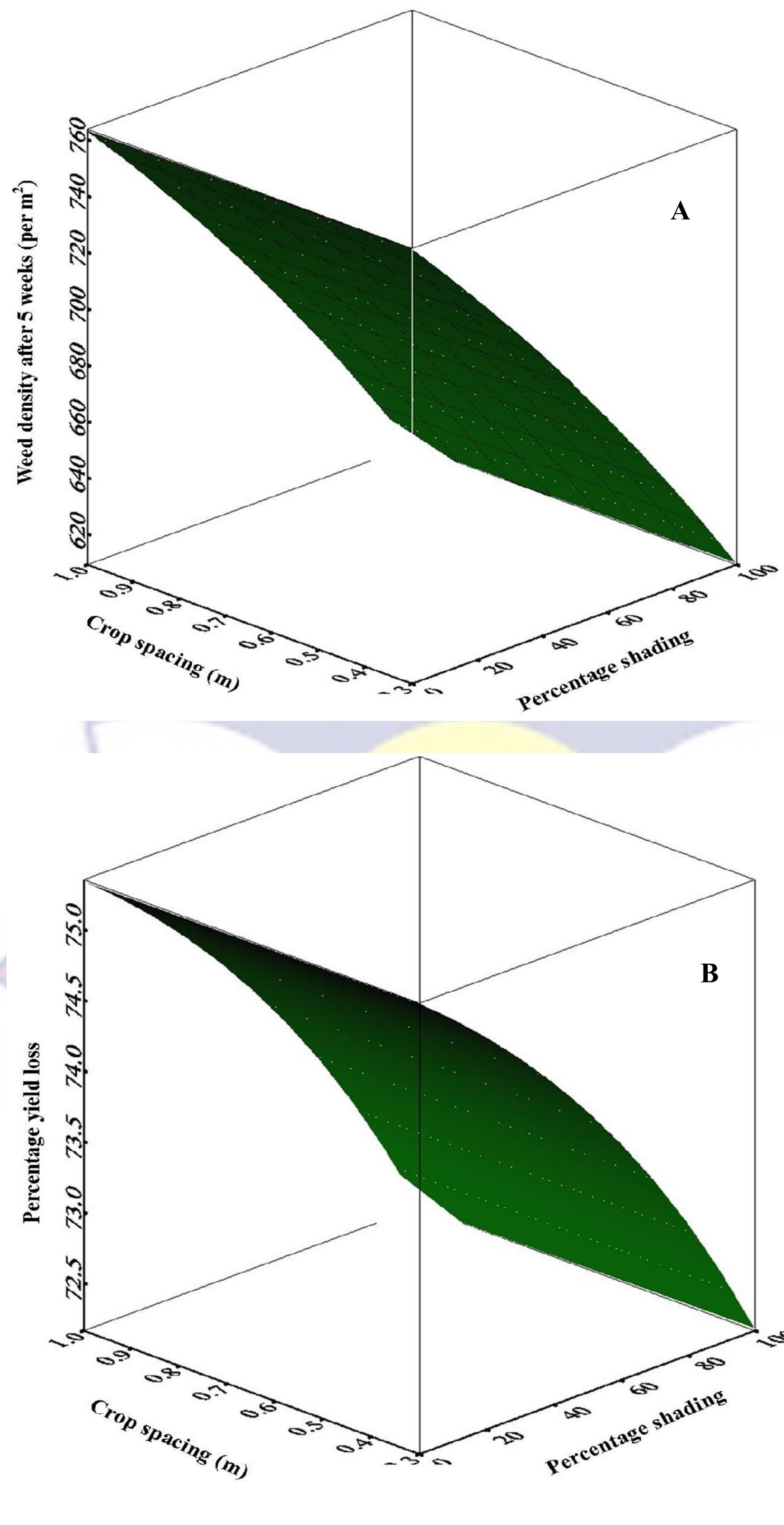


Figure 35: Effect of integrating shading with crop spacing on weed density after 5 weeks (A) and percentage yield loss (B)

Integration of integrating reduced initial viable tuber density with control methods imposed after weed emergence

Reduction of initial viable tuber density and the imposition of other weed control methods after weed emergence gave some levels of control but were still not adequate in reducing cabbage yield loss to the barest minimum. Thus a combination of the two was considered. However, as stated earlier, the timing of the imposition of the other control method is also crucial in ensuring a successful control of the weed. Figures 36, 37 and 38 show the output from the model for the integration of the two methods with the latter imposed 1 week, 3 weeks and 5 weeks after weed emergence respectively. They are based on the assumption that the weed population grows at the expected rate prior to the imposition of the control method. The outputs are indicative of some interaction effect of the two which increases as the timing approaches the critical competition period, (5 weeks after planting), hence the best result is attained when the control is imposed during the critical competition period. This, however may not depict exact reality as the model assumes that the yield loss is dependent only on the weed population during the fifth week. Some minimum level of loss may be caused before the period. Thus farmers need not wait till the fifth week before weeding their fields, even though it is critical to ensure that the field is weed free during that period as indicated by the output. The best approach in adopting the strategy, as indicated by the model, is first to reduce the initial viable tuber density to approximately 50 per m^2, minimize the weed population growth within the first few weeks and ensure a weed-free critical period of competition.

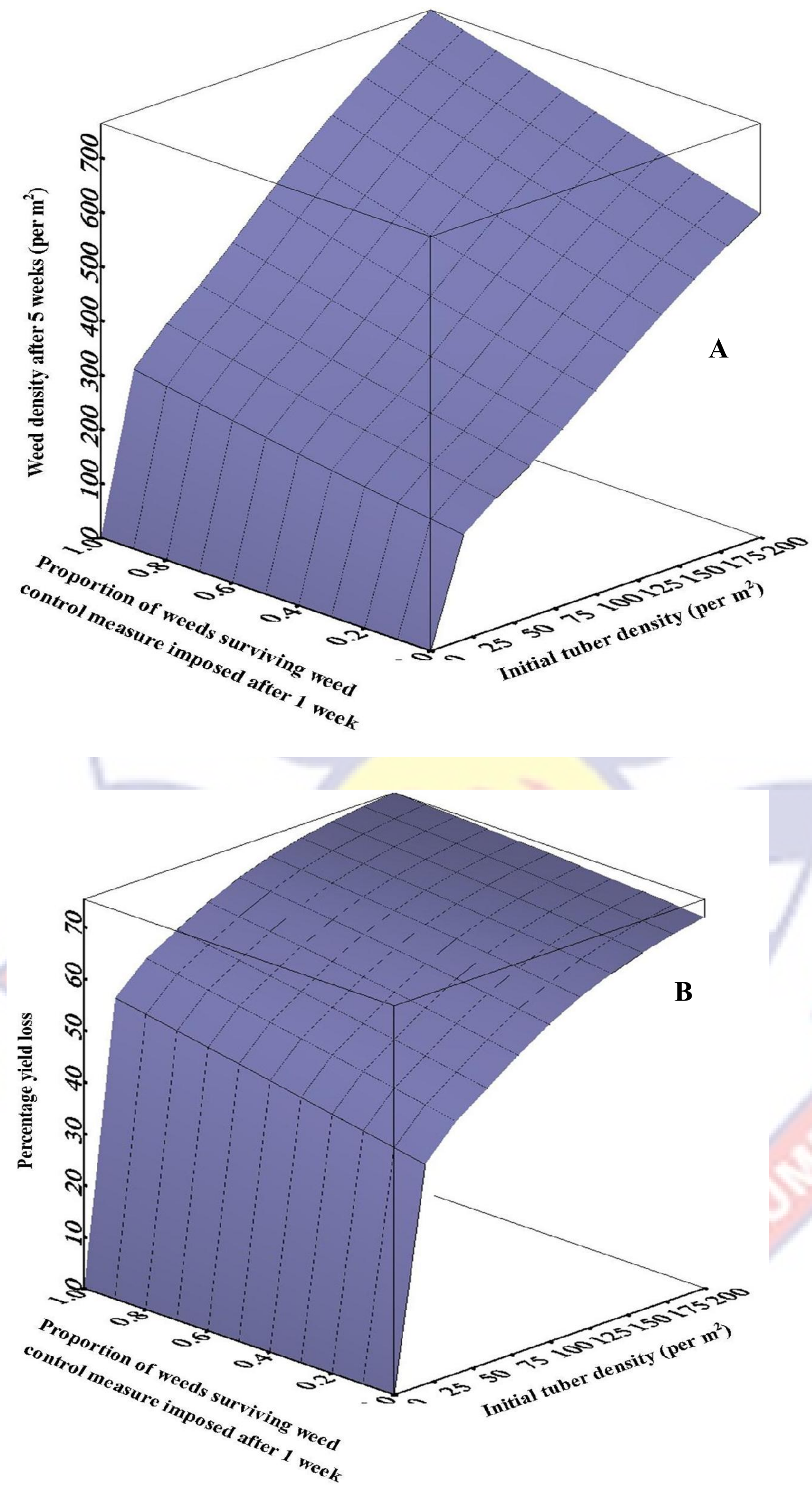


Figure 36: Effect of integrating reduced initial viable tuber density with a weed control method imposed 1 week after plant on weed density after 5 weeks (A) and percentage yield loss (B)

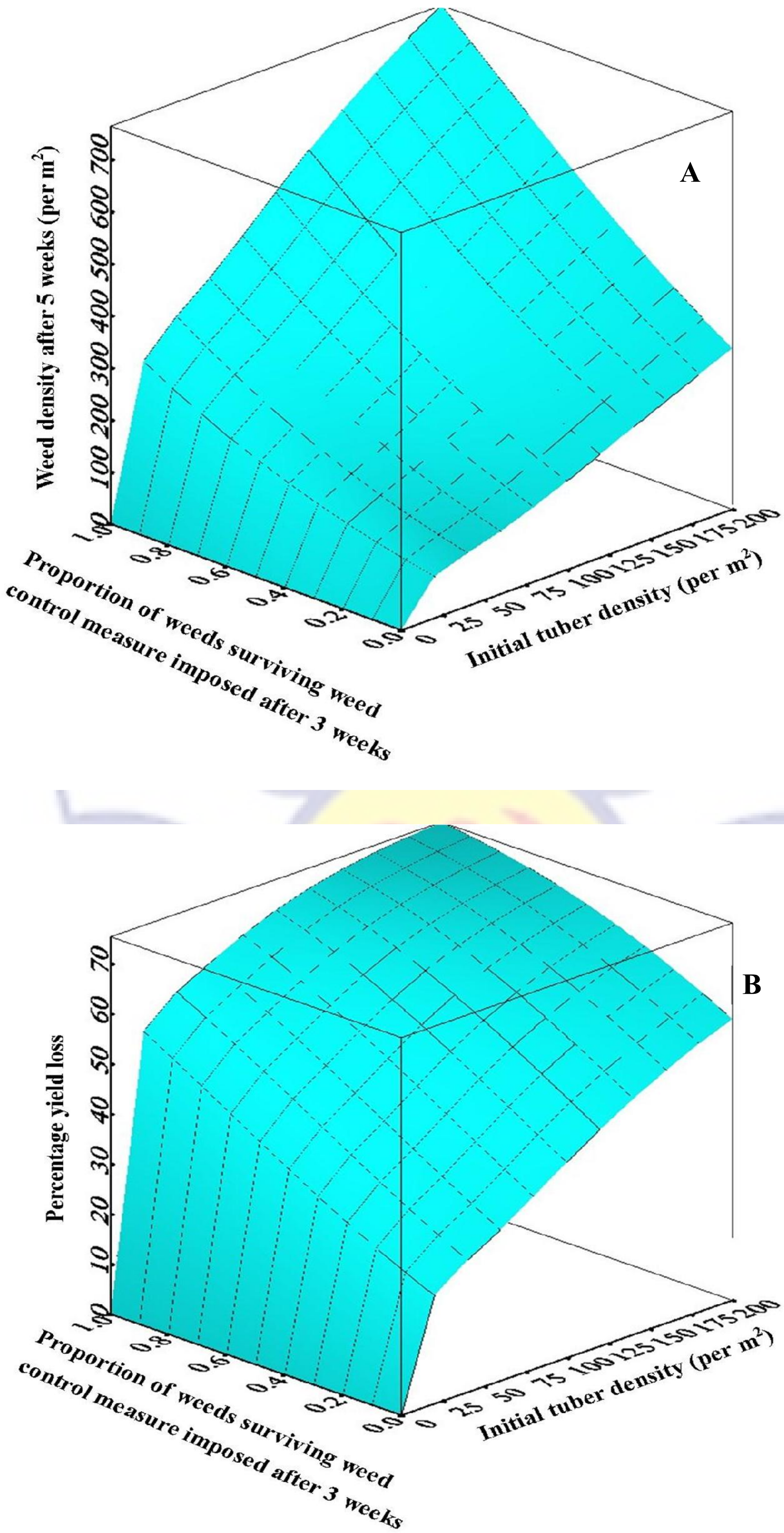
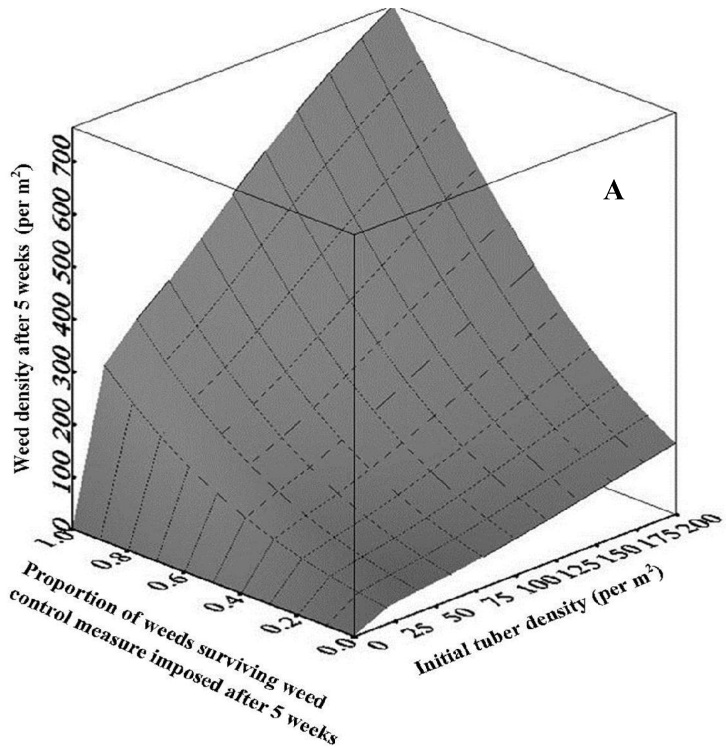


Figure 37: Effect of integrating reduced initial viable tuber density with a weed control method imposed 3 weeks after plant on weed density after 5 weeks (A) and percentage yield loss (B)



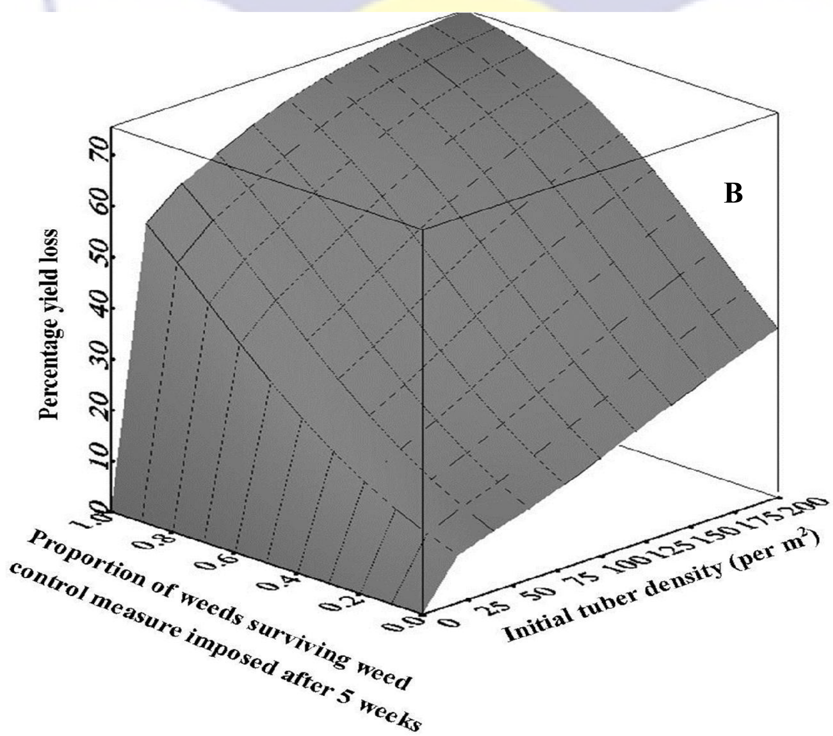


Figure 38: Effect of integrating reduced initial viable tuber density with a weed control method imposed 5 weeks after plant on weed density after 5 weeks (A) and percentage yield loss (B)

Summary

Outputs from the model so far show that out of the five parameters which could practically be used for the control of the weed, the initial viable tuber density was the most sensitive; implying that effective control of the weed should focus more on agronomic practices that reduces tuber population and viability instead of post-planting weed control. This confirms the statement by Neeser et al. (1998) that effective control of purple nutsedge requires the elimination of the tubers prior to planting. Reduction in initial viable tuber density can be achieved through site selection where various site options are available, manually picking out the tubers after tillage (where the field is small enough to make this approach feasible) or employing management methods that can effectively reduce the tuber population on heavily infested fields before planting. Management practices that destroy purple nutsedge tubers include exposing the tubers to desiccation in the dry period by tillage practices, (Leihner et al., 1984; United States Department of Agriculture & Natural Resources Conservation Service, 2000) and the use of systemic herbicides that can effectively reduce tuber density. For example, Doll and Piedrahita (1977) reported that five applications of 2, 4-D at 30 day interval with intermittent soil disturbance reduces tuber population by 86%, whereas three applications of glyphosate with intermittent tillage also reduces tuber population by 72%. The method used, however, is required to reduce the initial tuber density to negligible levels if it is to be used alone. This however may not be feasible, hence reduction in initial viable tuber density alone, may not practically manage the weed effectively and would have to be aided by another method in an integrated weed management system. Integrating of reduced tuber density with shading before planting, (as in the use of black plastic mulch or a thick layer of dry leaves) or other control measures imposed within the first five weeks after planting will give a very effective means of controlling the weed and improving yield.

Other parameters such as use of shading and the imposition of control measures after planting were proven not to be effective when used alone. Again, this is consistent with the suggestion by Doll (1994) that a single control method may not effectively control the weed. These methods however are effective when integrated with a reduction in initial viable tuber density. Crop row spacing, despite being suggested as a mean of control, was proven not to be effective (for the test crop, cabbage), neither when used alone nor when integrated with other weed management options.

Conclusion

The study has clearly demonstrated that purple nutsegde population in a vegetable field is affected by number of factors including initial number of viable purple nutsegde tubers, amount of soil moisture, percentage shading, intraspecific and interspecific competition and weed management measures employed by the farmer. However, effective management of the weed should be targeted at first reducing the number of viable tubers before planting and in combination with other weed management options instead of attempting to control the weed after the planting.

It is therefore clear that no single strategy can effectively manage the purple; an integrated approach would be best. The integrated approach should involve an effective means of reducing the initial tuber density of the purple nutsedge (for example, exposing the tubers to dessication and subsequent death by tilling the land in the dry and hot seasons, or using a systemic herbicide that effectively kills purple nutsegde tubers). Other methods that can effectively augment the initial viable tuber reduction include shading (for example use of mulches) and application of herbicides between three and five weeks after planting.

CHAPTER EIGHT

SUMMARY, DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

Summary

Vegetable production in southern Ghana suffers grave setbacks from several pests such as insects, nematodes and weeds. Prominent among the weeds is the purple nutsedge which was rated as the world's worst weed (Holm et al., 1977) and remains a major setback to vegetable production to date. Several attempts to identify effective but environmentally friendly management methods using the traditional weed research methods (which concentrate on the killing power of various chemical and mechanical control methods, and issues such as optimum time of application), have so far not been successful. Hence, this study was conducted to help in the design of efficient and environmentally sound management methods by developing an ecological model of the population dynamics of the purple nutsedge in vegetable fields of southern Ghana. Basically, the study sought to:

i. Gather baseline information on the prevalence of, and predominant methods of managing the weed in vegetable fields of southern Ghana. This was done to gain a fair idea of the current prevalence of the weed, methods of managing it, how effective these methods are, and also to help determine the kind of management methods that will be readily acceptable to the vegetable farmers. The study conducted by interviews and field assessments and is presented in Chapter four of this work.

ii. Assess diversity in the purple nutsedge in southern Ghana by morphologically characterizing collections of the weed from the study area. This was necessary in determining if the purple nutsedge from different locations were similar in terms of their biology and if they respond differently to management methods. This was to ensure that any proposed management method would work well for purple nutsedge across the study area. This study is presented in Chapter five of this work.

iii. Develop an ecological model of the population dynamics of the weed in the vegetable fields and its impact on the vegetables, and use it to identify effective environmentally sound management methods for the weed. The study was in two parts: the model conceptualization and the model parameterization, simulation and utilization, which are presented in Chapters six and seven respectively.

Having examined the various basic objectives in their respective Chapters, this final Chapter aims at synthesizing the findings so far in a bid to achieve the general objective of the study. It begins with a recap of the findings of the various sections, continues with a general discussion of the respective findings together, and finally concludes and recommends further studies and actions.

It came to light from Chapter three that land fallow, bush burning, fertilizer use and irrigation were common practices on vegetable fields in the study area. The major method of land preparation was by slashing and either hoeing or burning, with the use of simple tillage implements being the major means of controlling the purple nutsedge after planting. These practices were not deemed effective in controlling the weed.

Chapter four showed that even though some morphological characteristics of the weed varied with agroecological zones, probably as a result of morphological and/or physiological adaptions, on the whole, differences between purple nutsedge were not related to agroecological zones.

The study of the population dynamics of the weed in Chapters six and seven suggested integration any of means of reducing viable tuber density prior to planting, (such as tilling the land in the dry period or using systemic herbicide which effectively kill the tubers) and shading (use of mulch) or the employment of any management measure that effectively suppresses the weed within the first five weeks, as the best method of controlling the weed.

General Discussion

It is clear from the above recap that farmers concentrate on managing the weed after planting, contrary to the findings of this study which suggests that management of the purple nutsedge should focus on reducing viable tuber density before planting since management methods employed on heavily infested fields after planting would not be effective. It was also clear that land preparation methods employed could not effective reduce the viable tuber density.

Another weakness identified in the agronomic practices currently employed on vegetable fields was with the fact that land preparation which include some amount of tillage, was usually carried out at the onset of the rains. Tillage practices employed in dry periods expose the tubers to desiccation and subsequent death whereas the same practice employed in the wet period rather encourages the regeneration and proliferation of the weed. This would obviously promote the persistence of the weed on these fields.

One important issue which needed to be considered in this work was whether purple nutsedge across the study area would respond to management practices that would be recommended. However the study has shown that differences observed between samples collected from various locations in the study area were neither related to those specific locations nor their agro-ecological zones. Thus the proposed management method is expected to be effective across the study area. Again the proposed management method is expected to be environmentally friendly since it gives the timing for the application and the required efficacy of herbicide to use, where necessary, in order to avoid the abuse and misuse of herbicide which is detrimental to the environment.

Another major concern was with the readiness of the farmers to adopt and practice the new management practices that will be proposed. Again since the recommended management practices incorporate the already existing practices, it is expected to be easily adopted and utilized.

Conclusions

Purple nutsedge was well known among the farmers and was locally named after its closest edible relative, the tigernut (*Cyperus esculentus*) although very little was known about it use. The weed was reportedly present on the fields of more than 50 per cent of farmers interviewed and was said to be a problem weed all year round, especially in the wet season. It was generally rated as either the worst weed or among the worst by the farmers, who also indicated that it caused serious reduction in crop growth and yield. The major means of control was with the use of herbicides (prior to planting) and by the use of simple tillage implements after planting. These methods were said to be moderately adequate in managing the weeds

Among the agronomic practices examined, fertilizer use was found to be the only one that was related to the persistence of the weed. The weed was found to be more prevalent in the Coastal savannah and Transitional zones than in the Tropical Rainforest and Semi-deciduous and forest zones. The weed was also found to be negatively correlated with percentage Nitrogen, organic matter, clay and silt, and positively correlated with the percentage sand composition. No correlation was however found between the prevalence of the weed and phosphorus and potassium

The study also showed general conformation of the purple nutsedge in southern Ghana to those described for other parts of the world, except for the absence of rachilla. The weed, however, showed some amount of morphological and/or physiological adaptation to agro-ecological conditions. The major factors which determined differences in purple nutsedge in the study area were photosynthetic structures (involucral bracts and leaves), plant height and leaf characteristics. On the whole, differences observed in the morphology of the weed were irrespective of the agro-ecological zones.

The study further indicated that purple nutsegde population in a vegetable field is influenced by number of factors including initial number of viable purple nutsegde tubers, amount of soil moisture, percentage shading, intraspecific and interspecific competition and weed management measures employed by the farmer. However, effective management of the weed should rather be targeted at reducing the number of viable tubers before planting than after planting.

It was clear that only an integrated weed management approach could effectively manage purple nutsedge. The integrated approach should involve an effective means of reducing the initial tuber density of the purple nutsedge. Other methods that can effectively augment the initial viable tuber reduction include shading and application of systemic herbicides between three and five weeks after planting.

Recommendations

- Farmers with purple nutsedge infested fields should aim at managing the weed in the dry period before planting at the onset of the rains
- Multi-locational on-farm tests should be carried out to confirm the outcome of this study.
- Further studies should be carried out on the three-way competitive interaction between the vegetable crop, the purple nutsedge and other weeds, since the assumption of having only the vegetable crop and the purple nutsedge on the field does not always hold.

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APPENDICES

APPENDIX I: QUESTIONNAIRE FOR VEGETABLE FARMERS

A. FARMER DETAILS

Region…………… **District**…………… **Community**……………………

Name of farmer……………………………………

Tel:..

Age of farmer…………………………… (in years)

Sex Male [ ] Female [ ]

Education: No formal education [ ] Basic education [ ] Secondary [ ] Tertiary [ ]

Number of years engaged in vegetable farming …………………… years

Size of vegetable farm ……………………….. acres

B. CROPPING HISTORY

How long was this land fallowed before being cleared for cropping?

No fallow [ ] 6 months [ ] 1-2 years [ ]

3-4 years or more [ ] Not sure [ ]

Which crops were grown on this land over the past five cropping seasons?

Last cropping season ……..…………………………………………………

Last 2 cropping seasons ..……………………………………………………...

Last 3 cropping seasons.....…………………………………………………

Last 4 cropping seasons ..……………………………………………………

Last 5 cropping seasons ..……………………………………………………

How long has this land been cultivated continuously? ……. years

Did you burn the land before planting? yes [ ] no [ ]

How many times has this land been burnt over the last 3 years?

Once or twice [ ] between 3 and 5 times [ ] more than five times [ ]

C. HUSBANDRY PRACTICES

Please indicate the vegetable crops you grow? Tomatoes [ ]

Garden eggs [ ] Pepper [ ] Okro [ ] Cabbage [ ]

Lettuce [ ] Green pepper [ ] Carrot [ ] Others [ ]

Please specify ……………………………….

How did you prepare your land for planting?

Slash and burn [ ] Slashing and hoeing [ ]

Use of tractor [ ] Use of chemicals [ ]

What cropping system do you practice?

mono cropping [ ] mixed cropping [ ]

When were these crops planted? …………………………… weeks

Do you use fertilizer on your farm? Yes [ ] No [ ]

If yes what kind of fertilizer do you use? NPK [ ] Urea [ ]

Ammonium Sulphate [ ] Poultry Manure [ ] Cow dung [ ] Others [ ]

Please specify…………………………

At what rate do you apply the fertilizer per acre?

NPK………bags per acre Ammonium sulphate……bags per acre

Urea………bags per acre Poultry manure …………bags per acre

Cow dung ………bags per acre Other ……….. bags per acre

What is your source of water for irrigation?

Rain water [ ] Nearby stream [ ] Dam [ ] Dug out well [ ]

How do you control insect pests and diseases on your field?

Cultural control only [ ] Cultural, with minimum use of chemicals [ ]

Predominantly chemicals [ ]

If chemicals, please list them:……………………………………

How do you control weeds on your field?

Tillage tools (hand fork, hoe, etc) [ ] Slashing only [ ] hoeing [ ]

tractor plough [ ] herbicides only [ ] ridging [ ] Others [ ]

If herbicide, list them? ……………………………………………..

How do you apply them?..

What rate do you use?..

When was the first follow-up weeding done after planting?

………..weeks after planting

How many weedings do you do between planting and harvesting?

Once or twice [ ] between 3 and 5 times [ ] more than five times [ ]

D. FARMER'S PERCEPTION OF PURPLE NUTSEDGE

Can you identify the weed in Plate A? Yes [ ] No [ ]

What is the local name for it? …………………………………

What are the uses of the weed?..

Have you observed it on your farm? Yes [ ] No [ ]

Is it still on the field? Yes [ ] No [ ]

If yes, how long has it been on your field? ……………….. months

How do you rate the weed among other weeds on the field in terms of noxiousness?

The worst weed [ ] An important weed but not the worst [ ]

Not an important weed [ ]

Why? ……………………………………………………….…………

How do you control this weed? Tillage tools (hand fork, hoe, etc) [ ]

Slashing only [ ] Use of tractor [ ] Predominantly herbicides [ ]

Other (please specify)………………………………….

How effective is your control method? Excellent control [ ] Adequate control [ ] Inadequate control [ ] very poor control [ ]

When is the weed a problem? Wet season only [ ] Dry season only [ ]

Throughout the year [ ]

How does the weed spread from one field to another?..........................

What effect does it have on your farm? Reduces growth rate of crops [ ]

Reduce yield of crops [ ] Reduces market value of produce [ ]

Increases cost of production [ ]

Rate the % yield reduction on scale of 0 (no reduction) to 10 (total loss)

………………………………………………..

How does it affect quality?...

When does it effect the most damage if not removed? ………………….....

How much do you spend in controlling this weed? ……………….…….

On the average, how much of each vegetable do you harvest per acre?

……………..

How much do you sell your produce?..

Which other weeds are common on your field?

i.………………………………………………

ii.……………………………………………...

iii……………………………………………..

iv………………………………………………..

v………………………………………………

vi………………………………………………...

vii……………………………………………..

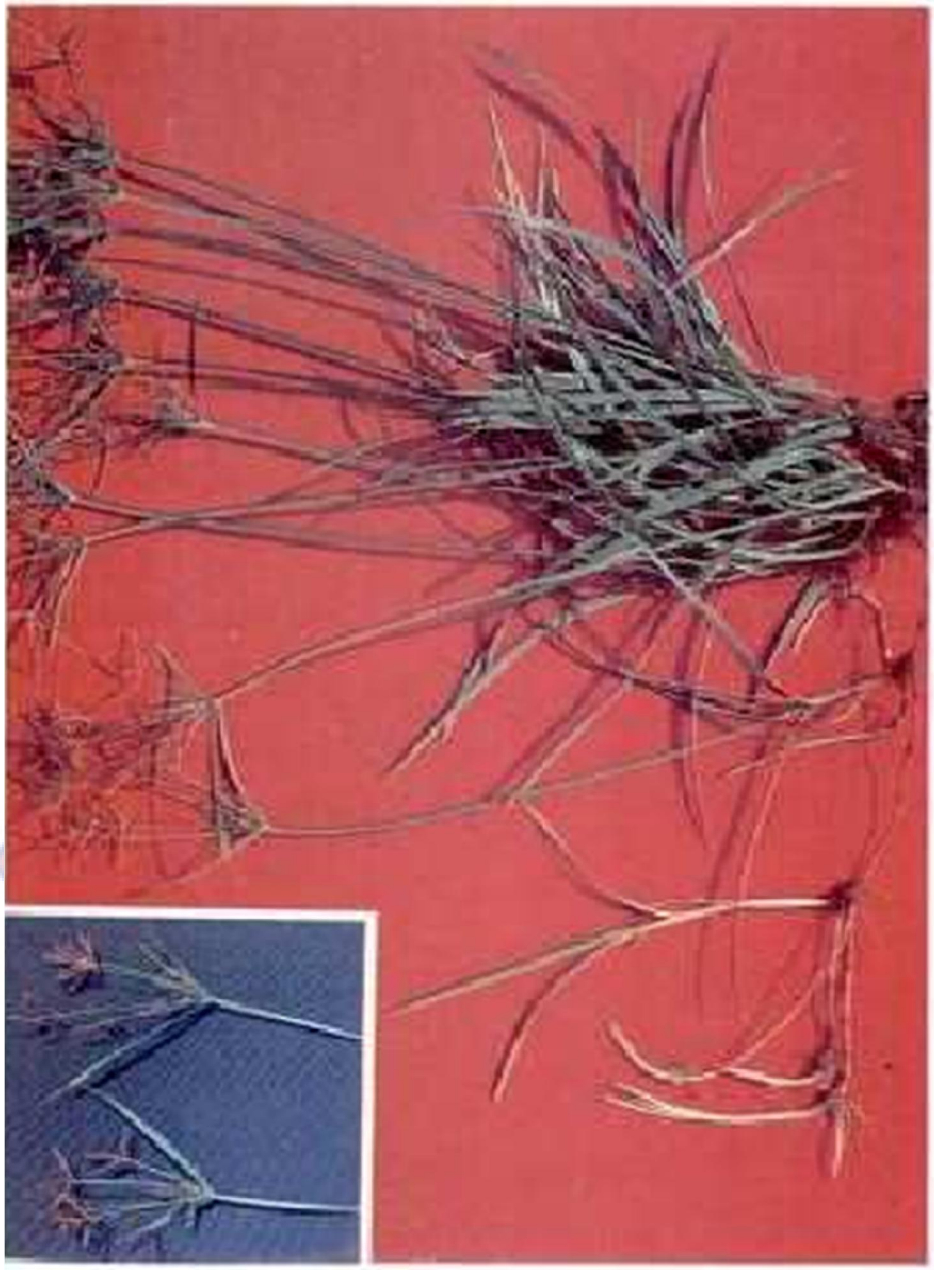
viii………………………………………………

ix……………………………………………...

x………………………………………………

Which of them are noxious?...

APPENDIX II: PLATE OF PURPLE NUTSEDGE USED FOR IDENTIFICATION



Adapted from Akobundu and Agyarkwa (1987)

APPENDIX III: SOLUTION TO THE DIFFERENTIAL EQUATION (EQ. 10)

From equation 10,

$$\frac{dP_t}{dt} = \beta\left(\frac{kP_t(K - P_t - \alpha_{wc}C)}{K}\right)$$

$$\frac{dP_t}{dt} = \left(kP\left(1 - \frac{P}{K}\right) - \frac{\alpha_{wc}C}{K}\right)\beta$$

Let $d = \frac{\alpha_{wc}C}{K}$ (since all are constants)

$$\frac{dP_t}{dt} = \left(kP\left(1 - \frac{P}{K}\right) - d\right)\beta$$

$$\frac{dP_t}{dt} = kP\left(1 - \frac{P}{K}\right)\beta - d\beta$$

$$\frac{dP_t}{dt} = k\beta P\left(1 - \frac{P}{K}\right) - d\beta$$

substituting

$$\frac{dP_t}{dt} = k\beta P\left(1 - \frac{P}{K}\right) - \frac{\alpha_{wc}C\beta}{K}$$

$$\frac{dP_t}{dt} = k\beta P\left(1 - \frac{P}{K} - \frac{\alpha_{wc}C}{K}\right)$$

$$k\beta.dt = \frac{dP}{P\left(P - \frac{P}{K} - \frac{\alpha_w C}{K}\right)}$$

$$\frac{1}{P\left(1 - \frac{P}{K} - \frac{\alpha_w C}{K}\right)} = \frac{1}{P\left(\frac{K - P - \alpha_w C}{K}\right)}$$

$$= \frac{K}{P\,(K - P - \alpha_w C)}$$

$$= \frac{K}{P\,(K - P - \alpha_w C)} = \frac{A}{P} + \frac{B}{K - P - \alpha_{wc}C}$$

$$K = A\,(K - \alpha_{wc}C - P) + BP$$

When $P_t = 0$

$$K = (K - \alpha_{wc}C)A$$

$$A = \frac{K}{(K - \alpha_w C)}$$

When $P_t = K - \alpha_{wc}C$

$$B = \frac{K}{(K - \alpha_w C)}$$

$$\frac{K}{P\,(K - P - \alpha_w C)}$$

$$= \frac{K}{(K - \alpha_w C)P} + \frac{K}{(K - \alpha_{wc} C)\,(K - P - \alpha_{wc} C)}$$

$$= \frac{K}{(K - \alpha_{wc} C)P} + \frac{K}{(K - \alpha_w C)\,(K - \alpha_{wc} C - Pt)}$$

Let K - $\alpha_{wc} C = \Phi$

$$\frac{K}{\Phi Pt} + \frac{K}{\Phi\,(\Phi - Pt)}$$

$$\int \frac{KdPt}{\Phi Pt} + \frac{Kd\Phi}{\Phi\,(\Phi - Pt)} = \int k\beta dt$$

$$\frac{K}{\Phi}\left(\frac{dPt}{Pt}\right) + \frac{dPt}{\Phi - Pt} = \int k\beta dt$$

$$\frac{K}{\Phi}\,(In\ Pt\ I - In\ I\ \Phi - Pt) = k\beta t + C$$

$$\frac{K}{\Phi}\, In\left(\frac{Pt}{\Phi - Pt}\right) = k\beta t + C$$

$$In\left(\frac{Pt}{\Phi - Pt}\right)^{K/\Phi} = k\beta t + C$$

Inverting

$$In\left(\frac{\Phi - Pt}{Pt}\right)^{K/\Phi} = k\beta t - C$$

$$\left(\frac{\Phi - Pt}{Pt}\right)^{K/\Phi} = e^{-k\beta t - C}$$

$$\left(\frac{\Phi - Po}{Po}\right)^{K/\Phi} = e^{-C} = A$$

$$\left(\frac{\Phi - Pt}{Pt}\right)^{K/\Phi} = Ae^{-\Phi\beta t}$$

$$(\Phi - Pt)^{K/\Phi} = (Pt)^{K/\Phi}\, Ae^{-\Phi\beta t}$$

$$(\Phi)^{K/\Phi} = (Pt)^{K/\Phi} + P^{K/\Phi} Ae^{-\Phi\beta t}$$

$$(\Phi)^{K/\Phi} = Pt^{K/\Phi}\,(1 + Ae^{-\Phi\beta t})$$

$$(P_t)^{K/\Phi} = \frac{\Phi^{K/\Phi}}{1 + Ae^{-k\beta t}}$$

$$P_t = \left[\frac{\Phi^{K/\Phi}}{1 + Ae^{-r\beta t}}\right]^{\Phi/K}$$

$$P_t = \frac{\Phi}{(1 + Ae^{-r\beta t})^{\Phi/K}}$$

$$P_t = \frac{\Phi}{(1 + Ae^{-r\beta t})^{\Phi/K}}$$

Where $\Phi = K - \alpha_{wc}\, C$

$$A = \frac{\Phi - P_0}{P_0}$$