PERFORMANCE AND MANAGEMENT OF INTER-SEEDED COVER CROPS IN A TROPICAL SEMI-ARID COTTON CROPPING SYSTEM AND IMPACT ON COTTON YIELD AND WEED SUPPRESSION

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ABSTRACT

Field trials were conducted in the Vidarbha region of India to investigate the potential for inter-seeded cover crops in monocropped cotton and evaluate 5 cover crop species for this purpose. The focus was to understand (1) the effects on cotton (yield) and weeds and (2) the performance of the cover crops themselves. After the living mulches were planted, no further inter-row cultivations or herbicide applications were carried out. Cover crop stands were cut back when needed to prevent shading of the cotton canopy. Cover crop biomass production of more than 80 tons ha^{-1} were observed, however, there were no significant effects of the system on cotton yields. Sunnhemp was the most promising species among those evaluated; following good emergence, when the cover crop received 1 to 2 weed-free weeks during the initial growth period, weed densities less than $15/m^2$ and weed cover as low as 7% were recorded.

BIOGRAPHICAL SKETCH

The author grew up in Kochi, India. In 2010, Vinay graduated from the Kerala Agricultural University with a Bachelor of Science in Agriculture (B. Sc. Ag) degree. After classes in many different disciplines of plant and agricultural sciences, he found his interest in the cropping pattern and weed management aspects of crop production. The practical crop production classes helped Vinay focus his interest to the development of innovative, economical and sustainable strategies for field management. Following a few months at an extension office dedicated to black pepper farming, Vinay began his graduate work at Cornell in 2011, in Dr. Robin Bellinder’s weed science program. Taking this Master’s work forward, Vinay plans to pursue a doctoral degree, focusing on management of living mulches in vegetable systems of the Northeastern United States using reduced-rate herbicide applications.

This work is dedicated to family, friends and farmers.

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CHAPTER I

Review of Literature

Introduction

Before herbicides became ubiquitous with weed management, textbooks on weeds in the early 1900s gave much importance to green manuring and cover cropping for soil fertility and weed control (Pieters 1927). In warm tropical climates (like in Central India), the long growing season has the potential to support higher intensities of cropping; and cotton (*Gossypium hirsutum* L.) grown in rotation with actively growing sunnhemp, can yield more than conventionally grown cotton (Reeves and Delaney 2002).

Because of high returns from cotton, it is often grown in monoculture (Reeves 1994) and this fear of yield losses is another reason why growers are hesitant to adopt inter-seeded cover cropping practices. Crop yield losses in broccoli (*Brassica oleracea* L. var. *botrytis* L.) (Brainard and Bellinder 2004) and in corn (*Zea mays* L.) (Reddy and Koger 2004) have been reported when cover crops were allowed to grow as living mulches; however in warmer regions, cover crops improve crop growth through soil moisture conservation (Gallagher et al. 2003) and reduced soil temperatures (Hutchinson and McGiffen 2000).

Cotton produces little residue, which makes preservation and addition of plant residue through conservation tillage and cover cropping necessary in cotton production systems (Causarano et al. 2006). Today, cotton factories are highly mechanized and the price a grower gets for cotton depends not only on the amount of cotton, but also on its quality. Studies in the U. S. A. have recorded better fiber qualities with adoption of mulching practices (Daniel et al. 1999) and in Vidarbha, Blaise (2006) reported that reduced tillage systems do not adversely affect fiber quality.

Nitrogen fixed by legume cover crops that are grown alongside long duration cash crops, will be available to the cash crop later in the season (Ofori and Stern 1987). In a cotton and pigeon pea (*Cajanus cajan* (L.) Millsp.) intercropped system on the semi arid vertisols of Vidarbha, Blaise et al. (2006) observed that adoption of conservation tillage and use of green manures increased both seed cotton yields and grain and pod yields in pigeon pea as compared to either recommended or farmers' practices.

Cover crops were grown as living mulches and not as winter fallow cover because establishment of cover crops after long duration crops like cotton (7 to 8 months) in a stressful environment such as in Vidarbha, will be poor and consequently, their survival into the harsh summer (February to May) that immediately follows. Growers who plant shorter duration crops cannot afford to give up a second crop in place of a cover crop stand.

Cover crops as intercrops/ living mulches and conservation tillage

Inter-seeded cover crops, merely as a consequence of their presence, would preclude the frequent inter row hoeing that is carried out for the duration of the growing season. Therefore, living mulch systems and reduced tillage systems have been discussed together because they go hand-in-hand. Many experiments on tillage and cover cropping in Australian cotton production systems have shown promise for conservation tillage and cover crops (Hulugalle et al. 1997; Constable et al. 1992; Triplett et al. 1996). Constable et al. (1992) and Hulugalle et al. (1997) observed increased cotton yields in reduced tillage systems, probably attributable to better soil water regimes that typically result from reduced tillage (Hulugalle et al. 1997; Triplett et al. 1996). However, from a no till experiment on alfisols, Reeves and Mullins (1995) reported that cotton was susceptible to compaction and that yield was improved by subsoiling as compared with no till. Raper et al. (2000) showed that such decreases in cotton yield with adoption of no-till could be reversed by addition of a cover crop.

Blaise and Ravindran (2003), from an experiment on tillage and residue effects on cotton in the Vidarbha region of Central India, reported that reduced tillage systems had lower weed biomass, greater plant dry matter accumulation, significantly greater number of cotton bolls and consequently, better yields. Small decreases in crop plant population due to vigorous growth and establishment of inter-seeded cover crops do not affect cotton greatly with regard to lint yields because, as a compensatory boll formation mechanism, individual plants make up for problems in crop stand (Reeves 1994).

One of the greatest challenges in introducing inter-seeded cover crops in a water-limited agro-ecosystem, with relatively infertile soils, is to reduce competition for water and nitrogen. Earlier studies in corn (Kurtz et al. 1952) and soybean (*Glycine max* (L.) Merr.) (Ateh and Doll 1996) have reported decreased levels of these resources in intercropped systems. "Agricultural conditions in warm regions make it difficult to prevent loss of soil organic matter and moisture, soil erosion and suppression of productive root and biological activity (Teasdale et al. 2007)"; hence introduction of cover crops in a region like Vidarbha is crucial and management strategies must be devised to control intercrop-cash crop competition. Besides reducing runoff, intercropping also results in higher surface moisture content during dry periods (Olasantan 1988) and lower rates of evaporation from the soil (Reddy and Wiley 1981).

Experiments have shown that even non legume cover crops do not vary in their growth performance with different nitrogen fertilization rates (Reberg- Horton et al. 2005), which means that legume cover crops would not necessarily need extra inputs or perhaps, not compete with the main crop for nitrogen. Residues with high carbon to nitrogen ratios will temporarily immobilize nitrogen (Sinha 1977) but, over time, this immobilization will reach equilibrium with nitrogen mineralization, causing reduced need for synthetic nitrogen inputs (Dinnes et al. 2003). Frequent mowing (to reduce transpiration), choice of legume living mulches (to minimize competition for nitrogen) and wide row spacing that is typical of cotton production systems, was expected to mitigate competition. Once the cotton canopy starts shading the cover crops, the resultant adverse effects on cover crop root development would also prevent competition with cotton (Fukai and Trentbath 1993).

Excess water and nitrogen fertilizers cause problems in production and quality of cotton bolls (Hearn 1975a; Hearn 1975b; Hearn 1976); so, additionally, vigorous growth of the cover crops in the rainy months could, to some extent, reduce the severity of water logging (common in the soils of Vidarbha) and thus, its adverse effects on cotton, through increased uptake and transpiration. Vigorously growing cover crops can rapidly take up water (Fukai and Trentbath 1993). However, even though there exists this nutrient and water competition with the main crop, the inputs of organic matter and reduced soil disturbance that result from having cover crops improve both biological and physical properties of the soil (Dabney et al. 2001; Hulugalle and Daniells 2005; Bruce et al. 1991). In a review of intercropping strategies, Fukai and Trentbath (1993) mention that it is possible, through management practices, to successfully manipulate the dominant intercrop such that the resources are available to the suppressed intercrop (cotton in the initial growth stages) in adequate quantities. Studies on light interception by sorghum (*Sorghum bicolor* (L). Moench) and legume intercropping systems have shown that greater light interception by the crops resulted in better weed suppression, better NPK uptake and better yields (Abraham and Singh 1984).

In long duration, widely spaced crops, grown in rainfed conditions in India, cropping systems with an intercropped legume resulted in better returns and with no significant effect on the main crop (Ali 1988). *Mucuna cochinchinensis* (Lour.) A. Chev., lablab (*Lablab purpureus* (L.) Sweet) and tropical kudzu (*Pueraria phaseoloides* (Roxb.) Benth.) have been reported to effectively suppress cogongrass (*Imperata cylindrica* (L.) P. Beauv.) when intercropped with maize (*Zea mays* L.) and cassava (*Manihot esculenta* Crantz) (Chikoye et al. 2001). Many cover crops have shown potential for adequate weed suppression without over reliance on pesticides (Carr et al. 1995). Unamma et al. (1986) showed that economic returns from an intercropped system were higher than from use of herbicides or hand weeding. In another study using purslane (*Portulaca oleracea* L.) as living mulch in broccoli, the yields were similar to that from conventional weed management strategies (Ellis et al. 2000).

Cover crops and conservation tillage in improving soil health

The introduction of inter-seeded cover crops calls for adoption of reduced/ conservation tillage, so this section will look at both independent and combined impacts of cover crops and conservation tillage practices on soil heath and fertility. Both cover crops and conservation tillage have excellent potential to mitigate effects of conventional tillage practices like soil erosion and to improve soil moisture conservation and organic matter (Sojka et al. 1991). Vertisols, on which the majority of the Indian cotton is grown, are a very challenging soil type to work with; when it is dry, it is intractable and when wet, it is sticky and unworkable; it is also highly susceptible to erosion from heavy rainfall (through surface run-off, because of poor infiltration rates when wet) and wind (Burnett 1985).

Hulugalle and Ezumah (1991) observed that lower soil temperatures that result from having intercrops increases earthworm populations, which in turn, improve water infiltration. Because cotton has a very slow initial growth phase, when mono-cropped, the between row spaces are still largely exposed during the onset of rains; inter-seeded cover crops reduce the erosive strength of raindrops and prevent soil detachment (Hartwig and Ammon 2002). Mutchler and McDowell (1990) reported that inclusion of legume cover crops in conventionally tilled cotton, decreased soil erosion losses from 74.2 Mg per ha to 20.4 Mg per ha.

Semi arid tropical regions like Vidarbha, have inherently low soil carbon (Tiessen et al. 1998) and use of crop residue as feed and fuel, water scarcity and incapacity of the soils to be highly productive prevents its increase (Paustian et al. 1997). Upland soils can lose all the original organic carbon in its topsoil in 127 years of cultivation (Harden et al.

1999). Thus, for agricultural sustainability in the region, it is of utmost urgency to conserve and add to the soil organic carbon pool. Use of cover crops, reduction of soil disturbances and fallow periods and better residue management can improve soil organic matter status (Lal et al. 1999; Follett 2001) while excessive tillage can accelerate decomposition of the organic matter (Hulugalle et al. 1997).

No till and increased organic matter content in the soil increase the fraction of soil macro aggregates (Fernandez et al. 2010), decrease soil strength (Raper et al. 2000) and improve water infiltration and retention (Alvarez and Steinbach 2009; Raper et al. 2000). Danso et al. (1991) reported that soil structure can be improved by addition of cover crops into the system. Soil organic matter increases linearly with an increase in the amount of biomass added to the soil (Larson et al. 1972; Rasmussen et al. 1980). Removal of crop residue and conventional tillage decrease soil carbon, increase wind erodible soil aggregates and reduce yield (Malhi et al. 2006). And in Vidarbha, crop residue available on the field after harvest is on a decline (Blaise and Ravindran 2003). Studies on cotton cultivation in the clayey soils of Australia have shown that increasing residues improves soil fertility and physical and chemical properties of the soil through increased organic matter content and reductions in dispersion index, plasticity and density of the soil (Hulugalle and Cooper 1994).

To maintain the levels of soil organic carbon, 2 to 3 kg/m^2 of dry matter needs to be returned to the soil but, in cotton production systems, the return is only 0.8 to 1.2 kg/m^2 (Hulugalle and Scott 2008). From a review of 20 studies on carbon fixation in cotton production regions of the Southeastern United States, Causarano et al. (2006) concluded that soil organic carbon in no-tillage systems increased by an average of approx. 195 kg/acre/year compared to conventional tillage and when no-tillage was practiced along with cover cropping, the amount of fixed soil carbon doubled. Such increases in soil organic matter in cotton when conservation tillage was included in cover cropping, was also reported by Mitchell et al. (2002). Minimizing tillage operations have also been reported to conserve soil organic matter in Australia (Hulugalle et al. 1997).

Cotton is susceptible to soil compaction (Mullins et al. 1992); however, inclusion of cover crops reduces the extent of compaction and mitigates the problems associated with it (Stirzaker and White 1995). Rochester et al. (2001) reported reduced soil strength/ compaction and slightly increased yields when legume crops were incorporated into the cropping system. Macropores formed by decaying roots, mitigate the adverse effects of intercultural operations on soil compaction (Reeves 1994). Kemper and Derpsch (1981) observed that compaction occurring during initial stages of adopting minimum tillage was greatly reduced by legume cover crops, which "seemed to have no difficulty in penetrating compact layers". They also found that cover crops were able to increase the water infiltration rates up to 628 percent.

Cover crops, living mulches and conservation tillage in mitigating agricultural pollution

Diversification of crops both temporally and spatially is important for sustainable agriculture (Wagstaff 1987). Cover crops, especially those inter-seeded as living mulches have excellent potential in conservation and low input sustainable agricultural management systems to reduce the load of agricultural chemicals because they reduce insect pests (Andow et al. 1986; Theunissen 1994; Pimentel 1961) and weed infestations (Liebman and Dyck 1993). They promote weed seed and insect pest predation by providing habitats to the predators like carabid beetles (Carcamo and Spence 1994; Davis and Liebman 2003; Reader 1991), whose populations are larger in polycultures than in monocultures (Carcamo and Spence 1994) and where there is good ground cover and abundant surface mulch (Clark et al. 1993). Cover crops also reduce weed biomass and seed production (Kumar et al. 2009). In vegetable crops, intercrops and living mulches were found to decrease insect populations (Andow et al. 1986; review by Theunissen 1994), although in cole crops, delays in maturation and reduction in head size have also been observed (Andow et al. 1986). Early studies on cole crops (Pimental 1961; Dempster 1969) have shown that populations of insect pests were lower in those grown with living mulches or weeds, chiefly because the species diversity provided alternate sources of food for the parasitic and predaceous fauna. Theunissen and den Ouden (1980) reported significantly decreased populations of caterpillars and aphids by intercropping brussels sprouts (*Brassica oleracea* L. var. *gemmifera* DC.) with cover crops.

Of the 28 billion rupees (450 million USD) worth of pesticides used in Indian agriculture, 16 billion (260 million USD) is spent only to control bollworm and sucking pests in cotton (Ghosh 2001); in such a situation, even a small reduction in this pesticide consumption because of natural pest control will be immensely beneficial to both growers and the environment. In summary, there is widespread agreement in the literature that reduced or conservation tillage (Carcamo and Spence 1994; House and All 1981; Lys et al. 1994), increased plant diversity (Carcamo and Spence 1994; Carmona and Landis 1999; Lys et al. 1994) and ground cover and surface mulch (Clark et al. 1993) all result in increased populations of natural enemies of agricultural pests; this makes a combination of living mulch and reduced tillage a viable technique in non chemical pest control (Brust et al. 1985).

Pesticide and nitrate leaching into groundwater is a source of concern today (Hallberg 1987; Ritter 1990). Movement of fertilizers and pesticides through surface run-off can be reduced with the help of cover crop mulches (Hall et al. 1984). Cover crops decrease this pollution from nitrogen fertilizers and legume cover crops have the capability to use excess nitrogen and suppress their own nitrogen fixation (Danso et al. 1991). In a review on cover crop effects on groundwater pollution, Meisinger et al. (1991) note that cover crops reduce nitrate leaching by using nitrogen both as a nutrient for growth and through the water consumed. Studies on intercropping have shown better uptake of nitrogen and potassium by crops due to increased populations of rhizosphere bacteria (Wahua 1984).

One other very important environmental function of legume cover crops is nitrogen fixation. Production of synthetic nitrogen fertilizers is not only an extremely energy consuming process but also uses fossil fuels as raw materials and releases large amounts of greenhouse gases (Bosch- Meiser and Haber processes); hence greater reliance on biological nitrogen fixation could reduce environmental pollution (Causarano et al. 2006). Cover crops in combination with conservation tillage can greatly reduce need for chemical nitrogen fertilization without compromising on returns (Dinnes et al. 2003). In this experiment, leaves of sesbania, gliricidia and sunnhemp decomposed rapidly upon mowing and as companion crops, the nitrogen released from this process can be utilized by cotton later in the season (Ofori and Stern 1987).

Soil organic carbon is the largest terrestrial pool of carbon (Batjes 1996) and as such, agricultural practices like conventional tillage and plowing that interfere with this carbon sink through hastened organic matter oxidation, can lead to escape of huge amounts of carbon dioxide into the atmosphere; in this respect, reduced tillage and cover crops help in improving the soil organic carbon content by preserving and adding to the pool respectively (Paustian et al. 1997; Lal et al. 1999; Follett et al. 2001).

Cover crops, living mulches and conservation tillage in weed management

Living mulches cannot be incorporated into the system without adopting no till for the duration of the cover crop stand; however, there is wide agreement in the literature that vigorously growing living cover crops will effectively suppress weeds (Akobundu et al. 2000; Blackshaw et al. 2001). Cover crops hamper weed emergence and weed seed production through competitive or allelopathic effects (Chou 1999; Liebman and Davis 2000; Weston 1996).

Living cover crops are better weed suppressors than dead residues (Teasdale and Daughtry 1993) because they compete with weeds at more phases of the weeds' life cycle (Teasdale et al. 2007). No till practices have been reported to have potential in weed seedbank depletion because they show higher weed seed germination (Gallandt et al. 2004). Further, Gallandt et al. (2004) concluded that almost half of the weed seedbank losses occurred due to 'fatal germination' and this can be exploited by inducing germination through primary tillage operations and subsequent management operations like mowing (Gallandt 2006) which could be an efficient technique in a living mulch cropping system. Temperatures of over 45 degree C are not uncommon in Vidarbha and the high temperatures that the topsoil gets heated to during the summer in reduced tillage systems, decrease weed seed survival (Egley 1990).

If there were no scarcity of below ground resources, an inter-seeded cover crop that is shorter than the cotton plants but taller and in greater density than the between row weeds, would adversely affect weed growth alone (through shading) because plants compete for light asymmetrically (Weiner 1990). Sometimes, as an adaption to competitive environments, weeds undergo rapid stem elongation (Sultan 2000; Schmitt

1997) by producing longer internodes (Ballare et al. 1987). Brainard et al. (2005) observed that Powell amaranth (*Amaranthus powellii* S. Wats.) in broccoli were twice as tall in the presence of inter-seeded rye, but, only had 18 percent of the dry weight of Powell amaranth in plots without inter-seeded rye. Hence, frequent mowing operations also take care of the weeds that escape smother by growing quickly up through the living mulch canopy, where light availability rapidly increases (Brainard and Bellinder 2004). These weeds can be managed in this fashion early in the season because weeds often exhibit shade avoidance mechanisms even before actual shading from the cover crop canopy (Ballare et al. 1987). This manner of mowing results in thicker and therefore, longer lasting surface residue, which, in turn, imparts longer weed suppression (Creamer et al. 1995).

Perennial weeds that propagate from below ground structures can be hard to control in reduced tillage systems (Koskinen and McWhorter 1986) however, the pressure that the between row mowing puts on below ground resources is enhanced by the fact that shade avoidance mechanisms trigger greater allocation of photosynthates to shoots than roots (Causin and Wulff 2003). Inter-seeded rye cover crops have been reported to produce as much as 95 percent shade between crop rows (Brainard et al. 2005). From an experiment conducted on *Circium arvense* (L.) Scop., Graglia et al. (2006) reported that, when grown with a competitive cover crop, six mowings reduced the aboveground biomass of the weed by 69 percent whereas, five hoeings only reduced the biomass by 49 percent. To summarize, frequent mowing of inter-seeded cover crops has the added benefit of efficiently managing the between row weeds and the shade avoidance mechanisms employed by these weeds contribute to the efficiency of this operation.

Weed control in dryland cotton production is difficult and its cost is high; hence, there is opportunity to improve on conventional weed management systems (Walker et al. 2005). In an extensive review of intercropping strategies for weed management, Liebman and Dyck (1993) describe intercropping, especially with rapidly growing cover crops, to be much better than sole cropping in many different aspects; also emphasizing its potential even in mechanized temperate agriculture, where it is already in existence in cereal legume mixtures like barley (*Hordeum vulgare* L.) and red clover (*Trifolium pretense* L.). Inter-seeded cover crops have been reported to reduce weed presence by over 90 percent (Carr et al. 1995). Liebman and Dyck (1993) found that in 90 percent of the cases, inter-seeded cover crops reduced weed biomass.

In cotton production, studies on Indian vertisols have reported that reduced tillage showed significantly fewer monocot and dicot weeds than conventionally tilled fields (Blaise 2006). Incompatibility of intercropping with agricultural machinery, which could be one of the biggest factors preventing the widespread adoption of intercrops, is chiefly because of the lack of attention that has been given to development of such machinery (Cordero and McCollum 1979; Vandermeer 1989). So, if the inter-seeding of cotton with cover crops is well advocated and well received among growers, there is hope that it might spark an interest in development of suitable machinery, which in turn, would make the whole system more efficient and appealing to growers. Inter-seeding with a cover crop can be designed such that it does not compete with, but complements the main crop and hampers only weed growth (Vandermeer 1989).

Even though there is the cost of establishing a cover crop stand, it is often more economic that non living mulches; Ellis et al. (2000) reported that using purslane cover crops as a living mulch was cheaper for weed management than black plastic and was not significantly different from conventional management. Residues from such cover crops can suppress weeds through allelochemicals (Wallace and Bellinder 1992; Weston 1996) and smothering effects (Teasdale and Mohler 2000). Reduced tillage studies in Vidarbha have exhibited promise for weed control in cotton fields (Blaise 2006).

As early as the 1930s, studies by weed ecologists (Brenchley and Warington 1933) have reported that in locations where there is continuous cropping of only one type of crop, weeds associated with it are usually those that have life cycles similar to that of the crop. Hence, weeds that infest cotton, often a long season crop of 6 to 7 months, could potentially be ‘exhausted’ or prevented from seed production (usually a big downside of cultural and non conventional weed management techniques (Jordan 1996)), by the frequent mowing operations that were carried out to manage the inter-seeded cover crops. The economic benefits of a weed management strategy over time is greatly influenced by the weed seed rain that it permits because large quantities of seeds can still be produced by a small population of weeds that might not affect the crop (Brainard et al. 2011) and weeds that experience a non competitive environment during their early growth produce larger quantities of seed (Brainard and Bellinder 2004). In this regard, cotton, a crop grown in rows as wide as 5 feet and with a non competitive early growth rate for 2 to 3 months, would benefit greatly in both short and long terms from being inter-seeded with cover crops, particularly those that can cover the exposed ground rapidly and as early as possible from when the cotton is sown.

Shetty and Rao (1981) reported that increased crop densities led to higher land equivalent ratios that resulted in better crop yields and reduction in weed growth. Brainard and Bellinder (2004) observed that weed biomass decreased with increase in cover crop density. Weed control is better when the cover crops are allowed to grow for the longest time possible (Blackshaw et al. 2007). The rapid initial growth of inter-seeded cover crops reduces nitrogen availability in the between row space and this deficiency, affects weeds more than the crop (Seibert and Pearce 1993) because crops can use their larger seed resources (Westoby et al. 1996); this technique can selectively suppress weeds early in the season (Liebman and Davis 2000), especially when fertilization is delayed (Angonin et al. 1996).

Weed suppressive abilities of grass legume mixtures are greater than grasses or legumes alone (Liebman and Dyck 1993) because of better resource capture (Clark et al. 1994; Fukai and Trentbath 1993). Grasses have been found to be quite competitive with weeds; Brainard et al. (2011) reported that where, in the absence of a cover crop, weed dry biomass was about 9 tons per ha with around 400,000 seeds per sq. meter, with a sorghum sudan grass (*S. bicolor* x *S. sudanese* (Piper) Staph) cover crop, the biomass decreased to just 1 ton per ha. Other studies (Teasdale and Daughtry 1993) have observed good weed suppression using live inter-seeded hairy vetch. Vigorous cover crops species like soghum sudan grass are particularly suited to warm climates where they can exhibit their full potential (Teasdale et al. 2007).

Brainard et al. (2005), from an experiment on the effect of cover crop canopy shade on Powell amaranth, reported that rate of leaf appearance, number of main leaves at flowering, fecundity, biomass and germination percent of viable seeds all decreased under competition. Such an inverse relationship between the rate of leaf appearance and flowering in weeds and the density of the canopy shading them, was also observed by McLachlan et al. (1993). Studies have shown that weed seeds that mature under such adverse conditions also have heightened dormancies; in a study conducted in Israel, Kigel et al. (1977) found that dormancies increased in seeds of redroot pigweed (*Amaranthus retroflexus* L.) that matured on plants that were exposed to low light and long days. In contrast, some plants like velvetleaf produce less dormant seeds under shade, along with a reduction in pod size (Bello et al. 1995). Inter-seeded cover crops often trigger shade avoidance reactions in weeds even before they actually start shading them; this is because of reduction in the red to far red ratio of light incident on the weeds due to horizontally reflected light from the cover crop (Ballare et al. 1987). Such responses could prevent flowering and seed set in a competitive environment (Smith and Whitelam 1997).

Brainard and Bellinder (2004) reported that if the inter-seeded cover crop was competitive enough, it could reduce weed seed production. Living mulches and residues can inhibit weed seed germination by reducing the diurnal change in light and temperature, thus simulating deeper soil conditions (Teasdale and Mohler 1993) and seedling emergence by physically smothering it (Teasdale and Mohler 2000). Also, unlike residue, living mulch has the ability to absorb red light (thus reducing red to far red ratio), which inhibits phytochrome-mediated germination of weed seeds (Teasdale and Daughtry 1993).

Cover crops establish better in infertile soils because they have larger seed reserves whereas, weeds (seeds) rely heavily on soil fertility for their initial development (Liebman et al. 2001) and do not compete well with legume cover crops in low N conditions (Staniforth 1962). What this means is that, replacing inorganic nitrogen inputs that stimulate vigorous weed growth (Blackshaw et al. 2003; Brainard et al. 2006; Schimpf and Palmblad 1980) with inter-seeded legume cover crops that provide 'slow-release' N to the crop during the growing season and also substantial amounts from its residue the subsequent season, it is possible to cut down weed infestations. Cover crop residues have been known to immobilize nitrogen (Dyck and Liebman 1994); this could prove to be detrimental to the between row weeds that might potentially not be able to compete with the inter-seeded legume cover crop.

In Vidarbha, every few years, organic matter is spread on the fields and incorporated before sowing of cotton. Such incorporation of organic matter before planting has been found to drastically favor weeds (Brainard et al. 2011) and organic matter in this region is usually raw manure (seldom composted). This results in severe weed infestation and their vigorous growth due to the growth stimulating media (manure) surrounding the weed seeds. Heavy soils like the vertisols of Vidarbha become extremely sticky and unworkable when wet; hence, timely weeding operations, carried out with bullock drawn hoes, becomes difficult during the rainy months and the excessive tillage carried out every year makes this situation worse (Blaise and Ravindran 2003). This hoeing, carried out in wet soil, further destroys the structure of the soil. Post- emergent herbicides for cotton currently available in this region are also limited.

The importance of legume cover crops as living mulches can also be potentially seen in pigeon pea which is another major crop in Vidarbha, with a similar cropping pattern to cotton but, with even wider rows and longer duration. Pigeon pea is widely fertilized with inorganic nitrogen fertilizers and this can cause decrease in nodulation

(Giller and Cadisch 1995); inter-seeded legume cover crops could be an ideal inclusion into this system. However, living mulch systems are much more complex and difficult to manage with changes required to be made in equipment or schedule of farm operations (Paine and Harrison 1993). Some studies have reported that they adversely affect crop establishment (Dabney et al. 1996) and create favorable conditions for weed seedling development by increasing nutrients and soil moisture (Teasdale and Daughtry 1993). In an inter-seeded cover crop study in transplanted broccoli, Infante and Morse (1996), found that living mulches were effective in controlling weeds and preventing yield decline only when weed pressure was low. Others have documented that they stimulate crop growth (Gallagher et al. 2003), especially in hot climates (Hutchinson and McGiffen 2000).

There has been a tremendous amount of work, over the past few decades, exploring this area of cover cropping; however, the literature on the performance and impacts of inter-seeded cover crops in a long duration crop, when managed by mowing in such a manner that they are non competitive with the main crop, but serve as living mulches throughout the season and on clayey, cracking soils of the semi arid tropics, is little and through this study, we expect to further our understanding in this specific area. The objectives of this experiment were to (1) understand the effects of inter-seeded cover crops on cotton growth and yield and (2) evaluate the performance of these cover crops in semi arid tropics and their effect on weed suppression and to study their potential for reduced tillage practices.

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CHAPTER II

Materials and Methods

Introduction

Field trials were carried out in Akola, a district in the Vidarbha region (Maharashtra State; 20.7°N, 77.07°E) of India, where cotton and soybean are the major crops. The experiments were conducted in cotton over two years at four different locations, hereafter referred to as Site 1, Site 2, Site 3 and Site 4. Sites 1 and 2 were chosen for the first year and all four were chosen for the second year. Site 1 was located at a research farm at the Panjabrao Deshmukh Krishi Vidyapeet (PDKV), the agricultural university for the region, while the rest of the sites were on private farms. Sites 2, 3 and 4 were located within approximately 2 to 5 kilometers of each other and were approximately 20 to 25 kilometers away from Site 1. The soil type at Site 1 was an inceptisol, at other sites they were deeper true vertisols. Only Sites 1 and 2 were analyzed for texture: Site 1 had silty loam soil (13.5% sand, 49.7% silt and 36.8% clay) and soil at Site 2 was a silty clay loam (7.9% sand, 44.7% silt and 47.5% clay). Soils at both Site 1 and Site 2 were alkaline with a pH of 7.8 to 7.9.

Field preparation and treatments

At Site 1, the field was first deep plowed (30cm) with a mold-board plow, followed by two harrowings (crosswise) using double-row disks. Partially composted and dried cow dung was broadcast over the field at 5 tons ha^{-1} and incorporated using a tractor driven flat pan implement. Two crosswise passes with the flat pan leveled the soil surface. The deep plowing and application of manure were done only for the first year; a shallower chisel plow (20cm) was used during the second year. At the on-farm trials, field preparation was similar but the harrowing and leveling were done using tractor-driven C-tined cultivators and bullock-driven wooden planks, respectively.

At all sites, the experiment was laid out as a randomized complete block design with five treatments and a control and four replications for a total of 24 plots at each trial site. At Site 2, the treatments were replicated only 3 times. Each plot measured 7.6m by 6.1m.

The treatments that were tested at each trail site during the two years are shown in Table 1. The control treatment at all sites was standard farmer's practice for the region (recommended practice in case of Site 1); these plots were not sown to cover crops and were kept weed free through hand weeding (Fig. 2.2). Sesbania (*Sesbania spp.*), gliricidia (*Gliricidia sepium* (Jacq.) Kunth ex Walp.), sorghum-sudan grass (*Sorghum bicolor* (L.) Moench x *Sorghum bicolor* (L.) Moench ssp. *drummondii* (Nees es Steud.) de Wet & Harlan), sunnhemp (*Crotalaria juncea* L.), lablab (*Lablab purpurea* L.), mucuna (*Mucuna bracteata* DC. Ex Kurz) and pueraria (*Pueraria phaseoloides* (Roxb.) Benth.) were the cover crops used. Cover crops were seeded at the following rates: sesbania-46kg ha^{-1}, gliricidia- 79kg ha^{-1}, sorghum sudan grass- 29kg ha^{-1}, sunnhemp- 57kg ha^{-1}, mucuna- 300g ha^{-1} and pueraria- 9kg ha^{-1} (Fig. 2.1; Fig. 2.5). Lablab was planted in two rows, 30 cm apart, at a plant-to-plant spacing of 30cm. Mucuna and pueraria did not establish in either plot the first year and therefore, were not used in the trials during the second year; these treatments are, therefore, not discussed further in this thesis. Only sesbania and sunnhemp were locally purchased and were readily available and inexpensive. Cotton used for the trials was *Bt* cotton, but different locally marketed cotton varieties were used at each site. The 'mixture' cover crop treatment used in the second year was a mixture of sesbania, gliricidia, sorghum-sudan grass and sunnhemp (11kg ha^{-1}, 26kg ha^{-1}, 11kg ha^{-1} and 14kg ha^{-1}, respectively). It was expected that this combination of species with their different growth characteristics would produce a faster, denser, cover and a more uniform stand for the length of the growing season.

An attempt was made to plant cotton and the cover crops on the same day; although circumstances did not always permit this. However, the cover crops were never sown before and no more than 2 to 4 weeks after cotton. Emergence of the different species following sowing was as follows: cotton, 5 to 7 days, sesbania, 4 to 6 days, gliricidia, 6 to 9 days, sorghum-sudan grass, 5 to 9 days, lablab, 3 to 4 days and sunnhemp, 3 to 4 days.

At all sites, cotton was planted in rows that were 1.5m apart, with 0.61m between plants; an exception was the second year at Site 2 where cotton row spacing was 1.2m and in-row plant distance was 0.46m. There were two plants per hill in the two field sites during the first year, but only at Site 1 during the second year. Cotton was seeded manually, which is the normal practice in the region. Bullock-drawn wooden tines were used to make furrows, 1.5m apart and approximately 5 to 6cm deep, in opposites directions across the fields; the cotton seeds were then placed at each intersection of these furrows. Two seeds were sown at each intersection and at Sites 2, 3 and 4 during the second year, these were later thinned to one plant per hill. At two plants per hill and a spacing of 1.5m by 0.61m, cotton was planted at 21,528 plants ha^{-1}.

After the cotton planting and in order to sow the cover crops, wooden tines were used to make four furrows (approximately 3 to 4 cm deep) between the cotton rows, 30cm apart from each other and from the cotton rows on either side (Fig. 2.3). The cover crop seeds were then manually seeded into the furrows (Fig. 2.1). At Site 1, during both years, this was done on the day of cotton planting; at other sites, cover crop seeds were sown 2 to 3 weeks after cotton planting. Because lablab seeds were much larger in size and lablab was grown as a marketable vegetable, it was seeded differently (Fig. 2.4). Lablab was dibbled 30cm apart in two rows, each 0.61m away from the nearest cotton row.

Management and Data Collection

Cotton at Site 1 was managed according to recommended practices for the region. At all on-farm sites, the growers treated the cotton in the experimental area similar to the rest of their field. Once the cover crops were sown, no more cultivation or hoeing was carried out in the plots. Frequent hoeing (5 to 7 times over the course of a season) between cotton rows using bullock drawn implements is common in this region and is targeted at weed control and prevention of soil surface crusting (Fig. 4.6). Typically, this is followed by hand weeding within the cotton rows. Since it was not possible to maneuver the bullocks and the cultivation tool through individual plots, control plots at all sites were hand weeded to keep the plots weed free.

For fertilization and pest and disease control at the on farm trials, the growers were requested to treat the experimental plots like the rest of their cotton field; however, herbicide application was restricted although their use in cotton farming is very uncommon in Vidarbha. Hand weeding was carried out every month in the cover crop treatment plots too, but only within the cotton rows.

The cover crops were allowed to grow as long through the season and into the following summer (February to May) as possible. The most important management operation in the trials was to cut back the cover crops every time they began to shade the cotton canopy, which was usually when they grew tall enough that they were only 20 to 30cm shorter than the cotton plants. Since the goal was not to kill the cover crops but to allow them to grow back and produce more biomass, they were cut back to a height suitable for their regeneration (approximately 30cm above soil level). The number of times the cover crops were cut varied between the species and the trial sites but was, on average, 3 to 5 a season. The mowed plant material was left as surface mulch where it fell and not distributed in any manner.

In 2012, the cover crops were cut back using a weed whacker fitted with a flail type nylon blade. This method was quick and effective, especially earlier in the season. The precision, however, dropped considerably with lateral branching and boll formation in cotton. The nylon blades also resulted in cuts not being clean and these frayed cuts led to too much mortality in the cover crop stands. Nylon blades were safer than metal blades because they did not damage the woodier cotton plants; whereas, metal blades sliced through them easily. Another problem encountered with the weed whacker was when the cover crops intertwined around the blades frequently enough that the operation became inefficient. This was especially true in case of sunnhemp, which is also grown for its fiber in several parts of India. In 2013, therefore, the weed whacker was replaced with garden shears in order to simulate mowing by a sickle-bar mower.

An exception to this management procedure was when using lablab, which was being tested as a potential marketable vegetable and as such, was trained on ropes and fertilized. Three bamboo poles of similar length were fixed in a line along the center of both the lablab and cotton rows (Fig. 2.4). Each pole had 3 holes drilled into it 0.61m apart and the plants were grown on plastic/ nylon ropes strung across the bamboo poles through the 3 holes. The lablab plots were kept weed-free like the check plots and the plants were not cut back but for removal of branches that climbed on the cotton plants. However, 2 to 3 months after sowing, because the poles could not bear the increased weight and because its encroachment into the cotton canopy was too severe, lablab became unmanageable and the plants had to be uprooted. The uprooted plants were laid down between the cotton rows as mulch. No yield was obtained from the lablab at any site.

Lablab plots were not sampled for any of the cover crop parameters. At other treatment plots, ground cover data was estimated through visual observations to gauge percent ground covers of both cover crops and weeds. The percentages were taken in absolute terms and so, percent ground cover of cover crops and weeds did not necessarily total 100%. Initially, these data were recorded 2 and 4 weeks after cover crop emergence; but subsequent observations were made immediately before the cover crops were cut back. Biomass samples were also taken before each mowing to estimate the amount of biomass produced. A $0.5m^2$ square quadrat was randomly placed between the 2 central cotton rows and all cover crop plants inside the square were cut at ground level, bagged and labeled; these sampled plants did not grow back. The number of cover crop plants in each square was also recorded in order to determine stand density. Four samples were collected from each plot and their average was used for the analyses. Plant material was weighed before and after drying in order to obtain both fresh and dry weights. Plants were oven-dried at 70°C for approximately 72 hours to determine dry weight.

The number of weeds in the sampling square was also recorded to obtain weed density. To get an estimate of the average height of cotton plants, the heights of 10 randomly chosen plants from the three middle rows of each plot were measured and averaged to obtain the mean height for each plot. These data were collected during later stages of boll formation, 130 to 150 days after planting. Using the same method, the average number of cotton bolls per plant in each plot was also estimated during the later stages of boll formation; some plots however, were sampled more than once to account for fresh prolific boll formation during harvest.

To measure cotton yield, the entire 3 middle rows of each treatment plots were harvested. Harvesting started in late October- early November and was continued approximately every 2 weeks until February. In order to collect the yield data, the entire three middle rows were harvested; harvesting was done by hand. Yields from all the pickings at each plot were then summed up at the end of the season to obtain the total yield for that plot. The number of cotton plants during harvest, due to various reasons, varied across different plots; so this parameter was recorded to obtain a final 'yield per plant' estimate. This was then used to calculate cotton yield in kg ha^{-1} for each plot using the planting density. The total number of plants in the three center rows was taken as the number of plants per plot since they were the only plants that were harvested for yield measurements.

At each individual site, the trial was set up in the form of a randomized block design. However, two cover crop treatments that failed during the first year were replaced with different species during the second year. Other cover crop treatments failed to establish at specific replications or sites. So, in order to understand the general effects of living mulches across trial sites, the data from all sites and years were combined for analyses; the design was a multi-level design in form of an incomplete block design with partial repeats on some treatments. Statistical analyses were carried out using 'JMP Pro 11.0.0 (© 2013 SAS Institute Inc.)' software. Analysis of Variance (ANOVA) and regression analyses were used to test for treatment effects, at 5% level of significance. Treatment differences were compared using the Tukey's HSD test.

FIGURES AND TABLES

Table 2.1. Cover crop treatments used at the different trial sites each year.

Treatment	Site 1		Site 2		Site 3		Site 4	
	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2	Year 1	Year 2
Control	X	X	X	X	-	X	-	X
Sesbania	X	X	X	X	-	X	-	X
Gliricidia	-	X	-	X	-	X	-	X
Sorghum sudan grass	X	X	X	-	-	X	-	-
Mixture	-	-	-	X	-	-	-	X
Lablab	-	X	-	X	-	X	-	X
Sunnhemp	X	X	X	X	-	X	-	X

Fig. 2.1. Cover crops (sudan grass in shown in this picture) planted in rows between cotton rows. Depending on the implements available to the grower, 3 or 4 rows of cover crops were planted between two rows of cotton.

Fig. 2.2. Hand weeded control plot.

Fig. 2.3. Furrows made for hand seeding of cover crop seeds.

Fig. 2.4. Lablab was tested as a marketable vegetable and was grown between cotton rows on ropes strung across bamboo poles.

Fig. 2.5. Sesbania (top), gliricidia (middle) and sunnhemp (bottom) treatments.

CHAPTER III

Cover Crop Effects on Cotton

Introduction

In the semi-arid cotton belt of Vidarbha in Central India, where the experiment was conducted, high temperatures, intensive agriculture and excessive tillage have resulted in soils that are severely depleted in organic matter. Current farming practices in cotton production remove above ground crop residue after harvest (January) for use as feed and fuel, thus exacerbating the problem of soil organic matter (SOC) depletion. To improve the physical and chemical properties of the vertisols in this region, there is an urgent need to increase SOC content to sustainable levels through its addition and preservation.

However, in the predominantly rainfed agriculture of the arid and semi-arid tropical regions, scarcity of water makes it difficult to establish a cover crop stand after a long duration crop like cotton. Late planting of cover crops would also shorten their survival into the hot and dry summer (February to May) that immediately follows the growing season (late May to late January). Summers in Vidarbha are very hot and dry; to such an extent that, even the small percentage of growers who have irrigation facilities seldom farm during this season. Even weeds do not come up in these dry months, leaving the soil barren and exposed to the sun. Growers who plant a shorter duration crop cannot afford to replace a second cash crop with a cover crop stand.

With the abundance of sunlight in this tropical region and a long growing season, there are opportunities to intensify a mono-cropped system (Reeves and Delaney 2002) and a slow growing cash crop can be inter-cropped with a living cover crop mulch. Living mulches provide numerous benefits to the entire agro-ecosystem. However, the strategies that are used to manage them differ vastly by region and can significantly influence the outcome of introducing them into a cropping system. Cotton takes 3 to 4 months to effectively cover the ground; this slow initial growth of cotton, early in the growing season provides excellent opportunity for the cover crops to become well established and be able to withstand the subsequent months of shading.

Field trials were carried out in the district of Akola in Vidarbha, Maharashtra State. Trials were established at 2 sites during the 1st year and at 4 sites during the 2nd year. The cover crops tested in the trials were sesbania (*Sesbania spp.*), gliricidia (*Gliricidia sepium* (Jacq.) Kunth ex Walp.), sorghum-sudan grass (*Sorghum bicolor* (L.) Moench x *Sorghum bicolor* (L.) Moench ssp. *drummondii* (Nees es Steud.) de Wet & Harlan), sunnhemp (*Crotalaria juncea* L.), lablab (*Lablab purpurea* L.), mucuna (*Mucuna bracteata* DC. Ex Kurz) and pueraria (*Pueraria phaseoloides* (Roxb.) Benth.). Mucuna and pueraria were seeded several times during the first year, but showed extremely poor emergence and growth; so, these species were not used during the second year and were replaced with gliricidia and lablab. For this reason, mucuna and pueraria treatments will not be discussed further in the following sections.

Cover crops were managed by mowing them when they began to shade the cotton plants. No herbicides were used for cover crop or weed control. The overall goal of introducing different cover crop species into this region was to improve soil health by increasing the levels of organic carbon in the soil. It was assumed that cover crop biomass added to the soil will increase SOC content. Perennial mulches and no-till practices were not employed because cotton is sensitive to soil compaction and requires subsoiling for good yields (Reeves and Mullins 1995). The objectives of the experiment were to determine the effect of inter-seeding cover crops on yield of cotton, weeds and performance of the cover crops. The discussion in this Chapter will pertain to the effects the living mulches had on cotton plant growth and yield. Cover crop parameters used for this evaluation were amount of biomass produced, extent of ground cover and stand density; cotton parameters included boll count, plant height and yield.

Results and discussion

Cover crops showed good emergence and covered the ground rapidly. In most treatments, complete cover was achieved in 3 to 4 weeks at all sites and at least two mowing operations were carried out before the cotton canopy began to shade the cover crops, which was 2 to 3 months from planting. Duration of the cover crop stand was different at different trial sites. In general, they began to dry up between late September and December. Moving through the living mulches during harvest was more difficult compared to the hand-weeded control plots, but the wide spacing typically adopted for cotton cultivation in this region and the low vigor of the cover crop stands late in the season, permitted a degree of mobility that was acceptable to the persons employed by the growers, who were paid according to the amount of cotton they harvested.

Cotton plant growth and yield were not affected by the cover crop presence on most occasions. Among the cover crops, sudan grass caused visible signs of competitive stress in cotton plants. In many sudan grass treatment plots, cotton plants showed yellowing and stunting; and bolls formed were few in number, small and dried up quickly. All cover crops, with the exception of lablab, had an erect growth habit, which did not interfere with the cotton canopy. Sesbania and sunnhemp exhibited oblique lateral branching in many plots after they were cut back. But, the continued mowing operations prevented severe disturbance to cotton plants. Labalab was not as manageable as expected and climbed on the cotton canopy in all plots; the cover crop was uprooted 2 to 3 weeks before boll formation and left on the soil surface as mulch.

In this chapter, the effects of the living mulches on cotton have been illustrated in two different sections: in Section 1, data from the different sites and years was analyzed separately; data from all sites and years was combined for analyses in Section 2 to provide a broader understanding of the potential for inter-seeding cover crops in this cropping system. To understand these effects, responses of cotton parameters, like plant height, boll count and yield, to amount of cover crop biomass production and extent of cover crop ground cover was examined.

To check for cover crop treatment effects, ANOVA was primarily used and comparisons between treatments were made using the Tukey's HSD test. Regression analyses were conducted to understand trends followed by cotton parameters in relation to cover crop behavior. In order to examine these relationships beyond regression testing, the amounts of cover crop biomass and extents of their ground cover were grouped into different levels. It was possible that the magnitude of cover crop parameters imposed different degrees of stress on the cotton plants. To find out if this competition was indeed significant, cotton growth and yield parameters corresponding to each of the following cover crop category were then compared against each other. Biomass produced by the cover crops were grouped into 0 (control), 0-10, 10-20, 20-30, 30-40, 40-50, 50-60 and 60-100 tons ha^{-1}. Extent of cover was categorized into 0% (control), 20-40%, 40-60%, 60-80% and 80-100%.

Section 1

Cotton, cover crop and weed behavior varied in certain aspects from one trial site to another. Treatment effects on cotton (yield, height and boll count) at each site have been analyzed separately in this section.

Site 1, Year 1

Treatments were not significantly different from each other with regard to cotton yield (p= 0.12; R^2= 0.47; Table 3.1). From a Dunnett's test, none of the cover crop treatments were significantly different from the control. Sesbania showed a rather low yield relative to other treatments (1052 kg ha^{-1}). This was probably because sesbania dried up early in the season (first week of September) and the plots succumbed to severe weed infestation (Table 4.4). Cover crops also did not have any significant effect on cotton plant height (p= 0.51; R^2= 0.7; Table 3.2) or cotton boll count (p= 0.24; R^2 =0.69; Table 3.3). Replications 1 (62.0 cm) and 2 (62.4 cm) had shorter plants than Replications 3 (72.4 cm) and 4 (71.5 cm). This was most likely because manure for the field was dumped close to Replications 3 and 4.

Across the trial, there was no effect of the amount of cover crop biomass on cotton yield (p= 0.024; R^2= 0.11), cotton plant height (p= 0.61; R^2= 0.02) or boll count (p= 0.52; R^2= 0.03) (Fig. 8- appendix). There were no statistical differences in cotton yields (p= 0.187; R^2= 0.4; Table 1- appendix), heights (p= 0.286; R^2= 0.34; Table 2- appendix) or boll counts (p= 0.516; R^2= 0.24; Table 3- appendix) between treatment plots that corresponded to the different ranges of cover crop biomass production. However, yield corresponding to 20- 30 tons ha^{-1} of cover crop biomass (856 kg ha^{-1}) was much lower than the others (Table 1- appendix). Sesbania was the only cover crop that belonged to this category. Weed presence of over 67% was likely the cause for this yield decline. Cover crop ground cover or density did not have any effect on cotton yield, height or boll count.

Site 2 Year 1

No significant effect of treatments on cotton yield ($p = 0.47$; $R^2 = 0.51$; Table 3.1), cotton plant height ($p = 0.92$; $R^2 = 0.06$; Table 3.2) or the number of bolls per plant ($p = 0.06$; $R^2 = 0.81$; Table 3.3) was observed. Yield or plant height from none of the cover crop treatments was different from the control, according to Dunnett's test. In terms of all cotton parameters, including yield, there was a steady decline from the first to the third replication. Average cotton yields were 1665 kg ha^{-1}, 1585 kg ha^{-1} and 1439 kg ha^{-1} and plant heights were 124 cm, 120 cm and 117 cm in Replications 1, 2 and 3 respectively. The main irrigation pipe ran behind the 3rd replication and water seeping from the joints caused a continually saturated soil condition in Replication 3 and a similar but, less severe condition in Replication 2, which was farther away from the irrigation pipe. This might have caused the deterioration in cotton plant health in these replications. The wet soil conditions also resulted in decreased weed growth (discussed in Chapter 4). Therefore, contrary to the norm, although weed presence was in the order: Replication 1> Replication 2> Replication 3, cotton yield and height followed the same order.

Mean yield from sesbania plots (1689 kg ha^{-1}) was higher than the mean yield from control plots (1666 kg ha^{-1}) (Table 3.1). Sudan grass had the lowest yield (1408 kg ha^{-1}), most likely as a result of weed infestation (due to poor emergence and patchy stand); weed ground cover in sudan grass plots was 59% compared to an average of 39% for the entire trial. Mean boll count in sesbania plots (28) was significantly different from the control (42) (Table 3.3); other treatment plots were not significantly different from each other. From regression analyses, none of the cotton parameters showed a significant response to amount of cover crop biomass (fresh) or extent of their cover.

Three biomass ranges were recorded in the field: 0, 0-10 and 10-20 tons ha^{-1}. Cotton yield, height or boll count corresponding to these ranges was not significantly different from each other ($p= 0.17$, 0.99 and 0.22, respectively; $R^2= 0.32$, 0.0034 and 0.28, respectively; Table 1- appendix, Table 2- appendix, Table 3- appendix, respectively). Mean yield from the 0-10 range plots (1703 kg ha^{-1}) was slightly higher than the mean yield from control plots (1666 kg ha^{-1}) (Table 1- appendix). Cotton yield (Table 4- appendix), plant height (Table 5- appendix) or boll count (Table 6- appendix) corresponding to different degrees of cover crop ground cover was not significantly different from each other. But, average boll count in the 80-100% range (28) was much lower than those in 0% and 60-80% (Table 6- appendix). This is, perhaps, because 80-100% ground cover was recorded in both the lower yielding Replications 1 and 2 whereas, 60-80% occurred only in the higher yielding Replication 1. Cotton plant canopy was dense at this site by late October-early November and ground cover was almost complete. Cover crop or weed presence at this time was almost negligible.

Site 1 Year 2

Treatments had a significant effect on cotton yield ($p= 0.01$; $R^2= 0.63$; Table 3.1) and cotton plant height ($p= 0.0001$; $R^2= 0.84$; Table 3.2) but no significant effect on the number of cotton bolls per plant (p= 0.17; R^2= 0.43; Table 3.3). In terms of yield, gliricidia plots (818 kg ha^{-1}) were significantly different from lablab (1354 kg ha^{-1}) and control (1265 kg ha^{-1}) (Table 3.1). This could be attributed to increased weed presence (especially in Replications 3 and 4) as a consequence of slower growth and establishment (discussed further in Chapter 4). Cotton yield was less than 750 kg/ ha in these replications with a weed ground cover of 30 to 40% (average for the site was 18%) and biomass (fresh) production less than 10 tons ha^{-1}. Lablab and the control plots were kept weed free.

Mean cotton yield across Replications 1, 2 and 3 were similar, Replication 4 measured about a quintal lower. Percent weed ground cover in Replication 4 (19%) was similar to other replications (16%, 23% and 15%) but biomass (fresh) produced was on average, 2 to 4 tons ha^{-1} lower than the other replications; average biomass production across the site was 12.5 tons ha^{-1}. It is unclear if this low cover crop biomass production and resultant reduced surface mulch/cover impeded vegetative growth and boll formation late in the season, but other differences between the replications could not be identified.

Cotton plant height was quite variable between the treatments (Table 3.2). Tallest plants belonged to lablab plots (150 cm) while shortest plants were in gliricidia plots (116 cm). Both these heights were noticeably different from the rest of the treatment plots (Table 3.2). These differences in height were discernable in the field too, especially the tall plants in lablab treatment plots. Biomass measurements were not made in lablab plots because lablab was tested as a marketable cover crop and grown on simple rope trellises. However, lablab growth was very vigorous and dense and the canopy was voluminous between the cotton rows. This phenomenon and probable causes are described in greater detail in Section 2 of this chapter. Sesbania and sunnhemp plots had very similar cotton yield, height and boll count (Tables 3.1; Table 3.2 and Table 3.3). Growth and performance of sesbania and sunnhemp were very similar (biomass production and ground cover; Table 3.4); this could have caused cotton plants in these two treatment plots to behave similarly.

Caused by wet conditions and water stagnation on the heavy clay soils (Fig. 3.12), there was a severe outbreak of black root rot (*Thielaviopsis basicola* (Berk. and Br.) Ferraris) among the cotton plants. This resulted in a lot of mortality across the trial site. Plenty of plants recovered from the disease but were weakened. Low yields at this site relative to others could perhaps be attributed to this incidence.

Site 2 Year 2

There was no significant effect of the cover crop treatments on cotton yield ($p= 0.54$; $R^2= 0.73$; Table 3.1) or cotton plant height ($p= 0.094$; $R^2= 0.77$; Table 3.2). The control and mixture treatments showed slightly higher yields than other treatment plots, although the difference was not statistically significant. But, treatments had a significant effect on the cotton boll count ($p= 0.03$; $R^2= 0.84$; Table 3.3). This apparent disconnect between number of bolls per plant and cotton yield was observed across trial sites also, as a response to cover crop biomass (Fig. 3.4; Fig. 3.5; Fig. 3.6). Data on cotton boll weight was not collected, but bolls in plots with vigorous cover crop growth were observed to sometimes grow larger in size, albeit fewer in number.

Sunnhemp plots had significantly taller cotton plants than sesbania or lablab (Table 3.2) and the plants were, on average, 8 cm taller than those from the control plots.

Like in lablab plots at Site 1 during the second season, this tall nature of cotton plants could be a response to dense/competitive intercrop growth. Biomass produced by sunnhemp at Site 2 during the second season (50 tons ha^{-1}) was, on average, about 20 tons ha^{-1} more than sesbania or the mixture. To check for effects of amount of biomass produced by cover crops on cotton plant height, a regression analysis was carried out. Graphs from the results showed that there was a definite trend but it was not significant ($p= 0.094$; $R^2= 0.35$; Fig. 9- appendix). However, biomass (fresh) production in the ranges 0, 20-30, 30-40,40-50 and 50-60 tons ha^{-1} were recorded and cotton plant height steadily decreased with decrease in amount of cover crop biomass: 50-60 (158 cm)> 0 (145 cm)> 40-50 (141 cm)> 30-40 (134 cm)> 20-30 (122 cm).

Amount of cover crop biomass and density of cover crop stand did not have significant effects on cotton yield or plant height. Extent of cover crop ground cover did not affect cotton yield but had a significant effect on cotton plant height. There was a significant increase in plant height with increase in cover crop ground cover ($p= 0.0497$; $R^2= 0.25$; Fig. 9- appendix). This is in conformity to the earlier discussion on increase in cotton plant height with increase in cover crop biomass production. All three cover crop parameters had a significant negative effect on cotton boll count: (fresh) biomass- $p= 0.006$, $R^2= 0.43$; percent ground cover- $p= 0.004$, $R^2= 0.46$ and density- $p= 0.0005$, $R^2= 0.65$. Number of cotton bolls per plant was significantly higher in the control compared to the cover crop treatments (Table 3.3). But, similar to Site 1 during this same season (Table 3.1; Table 3.3), decreased boll count in cover crop treatments when compared to the control (or among themselves), did not necessarily translate into lower yields. The mixture treatment, in this instance, had yields comparable to the control but less than half the number of bolls per plant (Tables 3.1 and 3.3). This could, at both sites, indicate that cover crop presence triggered formation of larger bolls in cotton.

Like during the first season, water stagnation was prevalent in Replication 3 and in part in Replication 2 but, was much more prominent in all cotton parameters. Cotton yield, plant height and boll count were in the order: Rep. 1 (3066 kg ha^{-1})> Rep. 2 (2589 kg ha^{-1})> Rep. 3 (1711 kg ha^{-1}); Rep. 1 (148 cm)> Rep. 2 (139 cm)> Rep. 3 (122 cm) and Rep. 1 (32)> Rep. 2 (28)> Rep. 3 (17) respectively. Wet conditions during this second season made water stagnation and soil saturation worse than it was during the first year. Presence of vigorous intercropped cover crops could, under such wet situations (and heavy soils), have a positive effect on the soil moisture status by removal of water from the soil through transpiration (Wagger and Mengel 1988).

Site 3

Cover crop treatments had a significant effect on cotton yield ($p= 0.018$; $R^2= 0.49$; Table 3.1) and boll count ($p= 0.0073$; $R^2= 0.54$; Table 3.3). There was no effect of treatments on cotton plant height ($p= 0.59$; $R^2= 0.66$; Table 3.2). There was a steady decline in cotton yield across treatments (Table 3.1); mean yield from control plots was the highest at 744 kg ha^{-1} while sudan grass plots recorded the lowest with just 456 kg ha^{-1}. Adverse effects of cover crop competition were noticed in sudan grass plots in 3 out of the 4 replications. It was especially bad in Replication 4 where, cotton yield was just 268 kg ha^{-1}. The negative outcomes were clearly discernable in the field; cotton plants in these plots were severely stunted with sparse canopies and small bolls that opened only partially and dried up prematurely. Yellowing and browning of the leaves was also rampant. Weed infestation was also high in sudan grass plots with weed ground cover 3 to 4 times that of the other cover crop treatment plots (Table 4.4).

Cotton yield at Site 3 was much lower than at other sites. This was primarily because cotton planting was immediately followed by acute wet conditions, which lasted long enough that the cotton seedlings were permanently affected. Soon after, the field was afflicted by both fungal and bacterial diseases.

Mean cotton plant height between treatments was very similar (Table 3.2). But, in terms of cotton bolls, control plots (19) had more number of bolls per plant than other treatments and sudan grass and the lowest (12) (Table 3.3). As in Site 2 during the same season, both cover crop biomass ($p = 0.025$; $R^2 = 0.25$) and cover crop ground cover ($p = 0.038$; $R^2 = 0.22$) had significant negative effects on cotton boll count. Cotton yield and boll count were very similar between replications, but plants in Replications 1 (60cm) and 2 (63cm) were shorter than those in Replications 3 (73cm) and 4 (72cm). The reason for this disparity could not be identified.

Site 4

Cover crop treatments had no overall effect on cotton yield ($p = 0.19$; $R^2 = 0.32$; Table 3.1), plant height ($p = 0.054$; $R^2 = 0.43$; Table 3.2) or boll count ($p = 0.95$; $R^2 = 0.05$; Table 3.3). However, mean cotton yield from sunnhemp plots (1940 kg ha^{-1}) was significantly more than that from lablab plots (1420 kg ha^{-1}) (Table 3.1). This yield from sunnhemp plots was also higher than the mean yield from control plots (1792 kg ha^{-1}). Cotton plants in sunnhemp (141 cm) and lablab (136 cm) plots were taller than plants in control (109 cm) and the mixture (107 cm) plots. Sunnhemp was also the largest biomass (fresh) producer with 52 tons ha^{-1} (Table 4.1). Treatments were not significantly different from each other with regard to boll count (Table 3.3).

Cotton at this site was planted ‘pre-monsoon’ in mid-May (with irrigation before the rains) and so, cover crops were seeded a month later. This early sowing also resulted in a healthy stand and cotton yield was good across this trial site. Marked differences in cotton yield, height or boll count were not present between the different replications.

No significant response of any of the cotton parameters was observed with amount of cover crop biomass. Cotton plant height, as in other sites, slightly increased with increase in cover crop vigor and biomass. Mean height of cotton plants in plots where biomass (fresh) production was between 30 to 100 tons ha^{-1} was 128 cm as opposed to 109 cm in control plots.

Section 2

To find out if response of cotton to the cover crop treatments varied between the two years of the experiment, an analysis was conducted using only the cover crop species that were tested during both years. There was no interaction between year and treatments ($p=0.93$) and cotton yields from control, sesbania and sunnhemp treatment plots in 2012 and 2013 were similar (Fig. 3.1). So, for further analyses, data from both years were combined to generate a broader understanding about the outcome of introducing living mulches into the cotton cropping system of Vidarbha and evaluating their potential.

Sorghum sudan grass was planted in two fields each year; however, an extremely poor stand at one site (Site 1) during the second year resulted in only data from Site 3 being collected (Table 3.6). This loss of one site could explain the large disparity in cotton yields in case of this cover crop treatment. There was also, overall, no difference ($p=0.75$) between cotton yields in Year 1 and Year 2; so, data from both years and all four trial sites were combined for analyses of cotton parameters.

There was no significant effect of the cover crops on cotton yield ($p= 0.24$; $R^2=0.82$); also, none of the treatments differed from one another with regard to cotton yields (Fig. 3.2). Although trial sites were not different in terms of treatment effects on cotton yield, Site 2 and Site 4 displayed overall good yields while, at Site 1, it was average and very low at Site 3 (Fig. 3.3) (Site 2- 1718 kg ha^{-1}> Site 4- 1425 kg ha^{-1}> Site 1- 1241 kg ha^{-1}> Site 3- 954 kg ha^{-1}). Performance of cover crops was excellent at Site 3 (Table 3.6; Fig. 4.1), but cotton yields were extremely poor. This was most likely the result of untimely planting during wet weather, which led to subsequent stunting and disease incidence in the cotton plants.

Within every trial site, cotton yields from the different cover crop treatments were similar to each other, but the amount of cover crop biomass produced by the different treatments varied considerably (Table 3.5). This indicates that cover crop vigor and growth did not adversely affect cotton. Because the cover crop treatments and cover crop performance did not have any negative impact on cotton yield (Fig. 3.3; Fig. 3.4), the cover crop management strategies used were effective in controlling intercrop competition for nutrients, sunlight and water.

Although cover crops did not have any effect on cotton yields, a trend was noticed between cotton yield and amount of cover crop biomass. Cotton yields exhibited a prominent decline until 16 to 18 tons ha^{-1} of cover crop biomass (fresh weight) (Fig. 3.4) and then, increased steeply until 30 to 40 tons ha^{-1}. Cotton yields corresponding to this level (30 to 40 tons ha^{-1} (fresh weight)) of cover crop biomass were, on average, higher than even the check plots (Fig. 3.2; Fig. 3.4). Similar results have been reported from other studies involving legume intercrops in cotton in vertisol soils of Vidarbha, where cotton seed yields from conservation tillage and use of green manures were higher than recommended practices (Blaise 2006).

Cotton yield at Site 3 was poor across the entire field; when this site was excluded, there was a significant positive correlation between cotton yields and the amount of cover crop biomass ($p=0.0002$; $R^2=0.24$; Fig. 7- appendix). Increased addition of organic matter from vigorous cover crop stands and macropores formed by decaying roots improve water infiltration and retention (Alvarez and Steinbach 2009; Raper et al. 2000). Cover crops can decrease nitrogen fertilizer losses by uptake of nitrogen through water (Meisinger et al. 1991) and nitrogen from living mulches in long duration crops will be available to the crop later in the season (Ofori and Stern 1987). Crop uptake of nitrogen and potassium is also better in a healthy intercropped system due to increased population of rhizosphere bacteria (Wahua 1984). These factors could explain the higher cotton yields in vigorous cover crop stands.

Extent of weed ground cover was negatively correlated to both the amount of cover crop biomass (p=0.0003; Fig. 6- appendix) and the extent of cover crop ground cover (p=0.045; Fig. 2- appendix). So, this initial decrease in cotton yields was likely due to high weed presence that resulted from poor cover crop vigor and consequent lack of adequate and timely ground cover. During dry weather towards the end of the growing season, dried weed debris from these treatment plots entangled with cotton in the lower levels of the canopy; this contributed to yield loss from indirect effects of the weeds.

Cotton yields were better or comparable to mean control yields between 30 to 55 tons ha^{-1} of fresh cover crop biomass. This level of biomass production also corresponded with the lowest levels of weed ground cover (Fig. 1-appendix). The steep drop in cotton yields beyond this biomass level was likely due to data from Site 3, where cotton yields across the entire field were poor and cover crop biomass greater than 50 tons ha^{-1} were common (Table 3.5). At other sites where cotton yields were much higher, cover crop biomass was seldom more than 50 tons ha^{-1}. The mean cotton yield corresponding to this level of biomass production was much lower (p=0.039) than cotton yields associated with other biomass levels (Fig. 3.5).

The lower cotton yields corresponding to 0 to 30 tons ha^{-1} of cover crop biomass (Fig. 3.4) corresponded with higher weed presence (Fig. 1- appendix). But, since treatment plots corresponding to cover crop biomass production beyond 30 tons ha^{-1} had good yields and better weed suppression (Fig. 3.4; Fig. 3.5; Fig. 1- appendix), this implies that weeds had the potential to cause yield declines in cotton and that the cover crops were able to prevent this in their healthy stands. This further indicates that cover crops themselves did not affect cotton yield, but rather, it was higher weed presence in their absence that caused cotton yield losses. Such asymmetric competition among plants has been established (Weiner 1990) and therefore, it is possible that the living mulches competed only with the weeds and not with the cotton.

To further understand the effect of the amount of cover crop biomass on cotton yield, the data was divided into groups. A Dunnett's test was performed to see if yield from any biomass group was different from the mean control yield. It was assumed that the amount of fresh biomass produced by a cover crop species would be better indicative of the amount of nutrients and water it competed for with the cotton. None of the groups, except the 60-100 tons ha^{-1} ($p= 0.025$), showed cotton yields significantly different from the control. This, again, was because the majority of data in the 60-100 tons ha^{-1} group were from the under-yielding Site 3 (Table 3.5). A better understanding of individual cover crop performance and associated cotton yields was obtained by graphing average cotton yield from each treatment corresponding to each of these cover crop biomass ranges (Fig. 3.5).

For similar reasons, in gliricidia and sudan grass treatments, where high amounts of biomass production occurred only at Site 3, cotton yields exhibited a decreasing trend with increase in cover crop biomass (Fig. 3.5) as the data points move from sites with better cotton yields to Site 3. However, low yields in gliricidia and sudan grass treatments were not restricted to Site 3; weed infestations also resulted in considerable yield losses in these treatments. At Sites 1, 2 and 4, emergence of sudan grass was patchy and sporadic and gliricidia was very slow growing. As a result, extensive weed growth led to both poor cover crop recovery and poor cotton yields. The most important observation from Fig. 3.5 was that yields comparable to that from existing cotton farming practices, or much higher, can be realized even with cover crop biomass production as high as 40 to 50 tons ha^{-1}.

With regard to cotton boll count, the living mulch treatments had no effect on the number of cotton bolls per plant (p=0.086). A slight negative trend in the boll count was, however, noticed with increase in cover crop biomass (Fig. 3.6). The different treatments (even within a site) showed variations in boll count (Table 3.5). But, there were no variations in cotton yields associated with these variations in the number of bolls (Table 3.5; Fig. 3.3). Further, there was no decline in cotton yields associated with increase in cover crop biomass. These factors suggest that good cover crop performance resulted in fewer but larger (heavier) bolls in those trial plots; this could explain the negative correlation of boll count with cover crop biomass (Fig. 3.6).

Cotton plants have the ability to compensate for the loss of nearby plants by growing bigger and thereby, achieving better yields (Sadras 1994). Perhaps, a similar physiological compensatory mechanism in response to cover crop presence is responsible for the adjustment in boll size. The ability of living mulches to moderate water and nitrogen availability to cotton plants might be another factor causing this behavior in cotton bolls. Water logging is a serious issue in the clayey soils of Vidarbha (Fig. ; here, vigorously growing living mulches can reduce its severity though rapid uptake and transpiration of this water (Fukai and Trentbath 1993). In a series of experiments conducted to understand the response of cotton bolls to water and nitrogen (Hearn 1975a; Hearn 1975b; Hearn 1976), liberal water and nitrogen availability resulted in smaller and lighter bolls. This was postulated to be because of stimulation of vegetative growth, which diverted assimilates from growing bolls to leaves. These bolls also had less fiber per seed and the lint was poor in quality and appearance. So, it was probable that a more competitive environment for water and slower release of nitrogen in case of cover crop treatments, during the boll filling stages, resulted in heavier bolls. Studies in the United States (Daniel et al. 1999) and in Vidarbha (Blaise 2006) have demonstrated that fiber quality improves with mulching and reduced tillage, respectively.

An analysis of cotton plant height data showed that treatments had no significant effect on the cotton crop ($p= 0.303$; Fig. 3.7). Mean height of cotton plants at each treatment and site is shown in Table 3.2 and Table 3.5. Effect of year was also not significant ($p= 0.576$). Although there were no statistically significant effects of the cover crops on cotton height, some variations between treatment plots were observed that were consistent across the trial sites (Fig. 3.8).

In treatment plots where cover crop stands were excellent, some changes in cotton plant growth were observed (Fig. 3.8; Table 3.6). There were several instances in sesbania, mixture, lablab and sunnhemp treatments where high biomass production was associated with taller cotton plants. Although this correlation was not observed in all cases, when checked for a trend, there was a slight increase (not statistically significant; $p=0.75$) in cotton plant height with increase in cover crop biomass (Fig. 3.9). This phenomenon was noticed in the field too. Sunnhemp and lablab were the two cover crop species that produced the most biomass and cotton plants were the tallest in these treatment plots at all the trial sites (Fig 3.8). Almost consistently, across all sites, the cotton plants in intercropped treatment plots were, on average, taller than the cotton plants in the check plots (Fig. 3.8).

After the end of monsoon rains in September, warm and dry conditions develop by November; by this time, 2 to 3 (boll) pickings would have been completed and the cotton plants would have begun to cease vegetative growth. However, in the aforementioned plots, cotton plants exhibited new apical shoot growth and subsequent boll formation. This extended the vegetative growth period by another 40 to 50 days to January and this increase in cotton plant height and new growth were easily discernable in the field. This phenomenon was probably because of a better soil moisture (or nutrient) profile that resulted from the presence of abundant surface mulch, combined with late-season loss in cover crop vigor that drastically reduced moisture losses through transpiration (Blevins et al 1971). In previous studies (Constable et al. 1992; Triplett et al. 1996), higher cotton yields have been observed in reduced tillage and cover cropped systems due to better soil water regimes in these systems.

And even though the cover crops were trimmed when they were 20 to 30cm from the top of the cotton canopy, perhaps, this was also an adaptation to a more competitive environment for light, especially at the lower canopy levels, as a consequence of dense inter-row vegetation (Sultan 2000; Schmitt 1997; Ballare et al. 1987). Living mulches can make nitrogen available to the crop later in the season (Ofori and Stern 1987); this additional nitrogen could have stimulated fresh cotton growth. Further, the newly formed cotton bolls were larger than earlier bolls. Similar observations with regard to boll formation were also reported from earlier experiments (1975a; Hearn 1975b), where the researcher postulated that assimilates from the extended duration of leaf production stimulated by nitrogen availability was transferred to the bolls, resulting in secondary thickening of the fibers. The corpulence of the bolls was also attributed to number of seeds rather than weight of lint per seed; although, continued growth leads to increase in weight of lint per seed (Basinski et al. 1971). Cotton requires a longer growing season to respond fully to the applied nitrogen and continued availability of nitrogen produces more boll growth (Basinski et al. 1971).

This taller stature made harvests easier and the extended vegetative period kept the soil surface covered longer into the hot months. These treatment plots did not suffer any significant yield losses compared to other treatment plots; many, on the contrary, gave relatively higher yields (Table 3.2; Table 3.5). In the production systems of southeastern United States, cotton grown in rotations with cover crops have recorded higher yields than from conventional practices (Reeves and Delaney 2002). During the dry harvest season, it was possible that the surface moisture content was higher in plots with copious amounts of mulch from the healthy intercrop stands (Olasantan 1988) and this increased water availability resulted in greater boll formation (Hearn 1975a).

Among the different treatments and sites however, there was one instance of clearly visible cover crop-cotton competition. This was noticed during the second year in 3 out of 4 sudan grass plots at Site 3 and was evidenced by severe yellowing and stunting of cotton plants followed by early drying and small, partially open bolls (Fig. 3.13). Where this treatment was most competitive, cotton plants had an average of only 7 bolls per plant and resulted in a yield of just 268 kg ha^{-1}. Kurtz et al. (1952) and Ateh and Doll (1996) have reported decreases in water and nitrogen in intercropped systems of corn and soybean, respectively. Perhaps, presence of competition in only the non-legume cover crop treatment indicates that the legume cover crops fixed enough nitrogen for their own growth and competition with cotton for nitrogen (and other nutrients) did not occur. Cover crop seeds were not inoculated before planting, however, good root nodulation was observed at all sites (Fig. 3.14). Competition for water was likely not the reason for poor cotton growth in the sudan grass treatment plots because all on-farm sites were irrigated until approximately a month before harvest.

To study the effect of cover crop ground cover on cotton yield, the percent ground cover data were grouped into ranges 20 to 40, 40 to 60, 60 to 80 and 80 to 100; there were no observations between 0 to 20% and percent ground cover for control was 0. Average cotton yield from the cover crop treatments falling into each of these categories were then used to create a graph (Fig. 3.10). Similar to the response to different levels of cover crop biomass production (Fig. 3.5), average cotton yields from many plots with robust cover crop stands were comparable to or better than that from the control plots. Lower yields in the 80-100 range was because most of the data came from the under-yielding Site 3. Slow initial growth and patchy emergence in gliricidia and sudan grass (respectively) were responsible for yield declines in those plots. From a Dunnett's test, none of these percent cover crop ground cover categories were significantly different from the control in terms of cotton yield.

There was no decline in cotton yield with increase in cover crop ground cover ($p=0.09$; $R^2= 0.04$; Fig. 10- appendix); there was however, a slight negative trend. Again, with cover crop stand density, cotton yields did not show any significant correlation ($p=0.26$; $R^2=0.02$; Fig. 3.11), but there was a slight positive trend. When data from Site 3 was excluded from the analysis, there was no noticeable change in the response of cotton yield to the extent of cover crop cover; but, with density of cover crop stands, cotton yield had a significant positive correlation ($p=0.028$; $R^2=0.093$; Fig. 3.11). These responses could be because a thinner cover crop stand, even with good ground cover, was likely not as effective against weeds as a denser stand. The large gaps between individual plants likely facilitated weed infestation. And as discussed previously, this increased weed presence could have caused the yield decline through both direct competition and by damaging the cotton lint with dry debris.

Cotton is a high value crop in the Vidarbha region and good weed management is critical for good yields. Current weed management by inter-row hoeing operations, however, consumes huge amounts of labor and destroys soil physical properties, especially because the bulk of this soil disturbance occurs during the wet period of the growing season. Present soil organic matter status also demands addition of organic matter and surface cover. Intercropping with vigorous cover crops have for long been acknowledged as a better alternative to sole cropping and as a good weed control technique (Liebman and Dyck 1993). The chief hindrances to adoption of living mulches are competition with cotton and inadequate weed control. This study demonstrated that the living mulches can accomplish the purpose of their introduction by producing large amounts of biomass and do so, without permitting weed infestation or affecting cotton yields.

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FIGURES AND TABLES

Table 3.1. Mean (LSD) cotton yields (in kg ha^{-1}) from the different treatments at each trial site and year. Letters denoting significance and the standard error refer to values down each column. Treatments connected by the same letter are not significantly different according to Tukey's test (α=0.05). Blank cells indicate that the treatment was not present during that Site-Year.

Treatment	Cotton yield (kg ha^{-1})					
	Site 1 Year 1	Site 2 Year 1	Site 1 Year 2	Site 2 Year 2	Site 3	Site 4
Control	1492(a)	1666(a)	1265(a)	2867(a)	744(a)	1792(ab)
Sesbania	1052(a)	1689(a)	1148(ab)	2334(a)	627(abc)	1803(ab)
Gliricidia	-	-	818(b)	-	713(ab)	1494(ab)
Sudan grass	1212(a)	1408(a)	-	-	456(c)	-
Mixture	-	-	-	2665(a)	-	1532(ab)
Lablab	-	-	1354(a)	2234(a)	481(c)	1420 (b)
Sunnhemp	1266(a)	1488(a)	1140(ab)	2176(a)	561(bc)	1940(a)
Std. error	120	164	93	532	59	161

Table 3.2. Mean (LSD) cotton plant heights (in cm) from the different treatments at each trial site and year. Letters denoting significance and the standard error refer to values down each column. Treatments connected by the same letter are not significantly different according to Tukey's test (α=0.05). Blank cells indicate that the treatment was not present during that Site-Year.

Treatment	Cotton plant height (cm)					
	Site 1 Year 1	Site 2 Year 1	Site 1 Year 2	Site 2 Year 2	Site 3	Site 4
Control	68(a)	121(a)	125(bc)	145(ab)	68(a)	109(b)
Sesbania	64(a)	117(a)	138(ab)	127(b)	64(a)	121(ab)
Gliricidia	-	-	116(c)	-	69(a)	127(ab)
Sudan grass	66(a)	124(a)	-	-	63(a)	-
Mixture	-	-	-	133(ab)	-	107(b)
Lablab	-	-	150(a)	126(b)	68(a)	136(a)
Sunnhemp	70(a)	119(a)	138(ab)	152(a)	70(a)	141(a)
Std. error	4	8.2	4	11	5	8.4

Table 3.3. Mean (LSD) cotton boll count (per plant) from the different treatments at each trial site and year. Letters denoting significance and the standard error refer to values down each column. Treatments connected by the same letter are not significantly different according to Tukey's test (α=0.05). Blank cells indicate that the treatment was not present during that Site-Year.

Treatment	**Cotton boll count (per plant)**					
	Site 1 Year 1	**Site 2 Year 1**	**Site 1 Year 2**	**Site 2 Year 2**	**Site 3**	**Site 4**
Control	23(a)	42(a)	64(a)	42(a)	19(a)	43(a)
Sesbania	18(a)	28(b)	53(a)	24(b)	17(ab)	41(a)
Gliricidia	-	-	61(a)	-	15(bc)	42(a)
Sudan grass	19(a)	33(ab)	-	-	12(c)	-
Mixture	-	-	-	19(b)	-	42(a)
Lablab	-	-	50(a)	21(b)	15(bc)	40(a)
Sunnhemp	20(a)	36(ab)	49(a)	23(b)	13(c)	42(a)
Std. error	2.4	4.3	5	6.3	1.2	2

Table 3.4. Average cover crop and weed parameters at Sites 1 and 2 from both years. Blank cells indicate the parameter was not measured.

Treatment	Site	Year	Biomass (fresh, tons ha^{-1})	Dry Biomass (tons ha^{-1})	Cover crop density (per $0.5m^2$)	Weed density (per $0.5m^2$)	Percent cover crop ground cover (%)	Percent weed ground cover (%)	Average height of cotton plants (cm)	No: of bolls/ plant	Cotton yield (kg ha^{-1})
Control	1	1	-	-	-	-	-	-	68	23	1492
		2	-	-	-	-	-	-	125	64	1265
	2	1	-	-	-	-	-	-	121	42	1666
		2	-	-	-	-	-	-	145	42	2867
Sesbania	1	1	15	2	31	18	68	52	64	18	1052
		2	20	3.6	14	-	83	25	138	53	1148
	2	1	7.8	1.2	14	-	67	58	117	28	1689
		2	31	4	42	5	70	15	127	24	2334
Gliricidia	1	1	-	-	-	-	-	-	-	-	-
		2	13	2.5	9.2	4.5	52	26	116	61	818
	2	1	-	-	-	-	-	-	-	-	-
		2	-	-	-	-	-	-	-	-	-
Sudan grass	1	1	19	3.1	12	11	61	55	66	19	1212
		2	-	-	-	-	-	-	-	-	-
	2	1	14	1.8	2	-	34	59	124	33	1408
		2	-	-	-	-	-	-	-	-	-

Table 3.4. Contd.

Treatment	Site	Year	Wet Biomass (fresh, tons ha^{-1})	Dry Biomass (tons ha^{-1})	Cover crop density (per $0.5m^2$)	Weed density (per $0.5m^2$)	Percent cover crop ground cover (%)	Percent weed ground cover (%)	Average height of cotton plants (cm)	No: of bolls/ plant	Cotton yield (kg ha^{-1})
Mixture	1	1	-	-	-	-	-	-	-	-	-
		2	-	-	-	-	-	-	-	-	-
	2	1	-	-	-	-	-	-	-	-	-
		2	34	5.7	14	4	53	18	133	19	2665
Lablab	1	1	-	-	-	-	-	-	-	-	-
		2	-	-	-	-	-	-	150	50	1354
	2	1	-	-	-	-	-	-	-	-	-
		2	-	-	-	-	-	-	126	19	2234
Sunnhemp	1	1	10	1.4	24	14	80	0.25	70	20	1266
		2	17	4	24	8	89	22	138	49	1140
	2	1	11.4	1.7	11	-	78	38	119	36	1488
		2	50	9	32	4.5	91	11	152	23	2176

Table. 3.5. Cover crop and weed parameters with corresponding cotton crop parameters across different trial sites and treatments. Missing values in all cover crop species except lablab indicate that they were not tested at that site/year. Lablab, being tested as a marketable cover crop, was kept weed free, as was the control. Letters denoting significance and the standard error refer to values down each column. Treatments connected by the same letter are not significantly different according to Tukey's test (α=0.05).

Treatment	Site	Fresh biomass (tons ha^{-1})	Dry Biomass (tons ha^{-1})	Cover crop density (per $0.5m^2$)	Weed Density (per $0.5m^2$)	Percent cover crop ground cover (%)	Percent weed ground cover (%)	Height of cotton plants (cm)	No: of bolls/ plant	Cotton yield (kg ha^{-1})
Control	1	-	-	-	-	-	-	97(a)	44(ab)	1441(a)
	2	-	-	-	-	-	-	119(a)	40(abcd)	1944(a)
	3	-	-	-	-	-	-	78(a)	20(cdef)	1144(a)
	4	-	-	-	-	-	-	94(a)	44(abc)	1618(a)
Lablab	1	-	-	-	-	-	-	111(a)	44(abc)	1215(a)
	2	-	-	-	-	-	-	113(a)	28(abcdef)	1634(a)
	3	-	-	-	-	-	-	82(a)	16(def)	871(a)
	4	-	-	-	-	-	-	112(a)	40(abcd)	1326(a)
Sesbania	1	17	2.74	26	14	76	38	100(a)	36(abcde)	1230(a)
	2	19	2.6	28	5	69	37	112(a)	27(bcdef)	1743(a)
	3	59	9.5	43	4	85	7.4	76(a)	15(def)	971(a)
	4	35	4	61	4.3	53	13	100(a)	39(abcde)	1466(a)

Table 3.5. Contd.

Treatment	Site	Fresh biomass (tons ha^{-1})	Dry Biomass (tons ha^{-1})	Cover crop density (per $0.5m^2$)	Weed Density (per $0.5m^2$)	Percent cover crop ground cover (%)	Percent weed ground cover (%)	Height of cotton plants (cm)	No: of bolls/ plant	Cotton yield (kg ha^{-1})
Gliricidia	1	13	2.5	9	4.5	52	26	88(a)	53(a)	1080(a)
	2	-	-	-	-	-	-	-	-	-
	3	42	7.7	16	3.2	75	10	78(a)	20(cdef)	864(a)
	4	10	2	14	6.6	32	21	103(a)	45(abc)	1293(a)
Sudan grass	1	19	3.1	11.6	11.4	61	55	100(a)	26(bcdef)	1160(a)
	2	13.5	1.8	2	-	34	59	120(a)	27(abcdef)	1618(a)
	3	39	6.2	16	4.4	48	28	77(a)	10(f)	848(a)
	4	-	-	-	-	-	-	-	-	-
Mixture	1	-	-	-	-	-	-	-	-	-
	2	34	5.7	14	4	53	18	108(a)	23(bcdef)	1803(a)
	3	-	-	-	-	-	-	-	-	-
	4	50	7.4	30	5.4	55	15	87(a)	38(abcde)	1453(a)
Sunnhemp	1	14	2.6	24	10.7	84	11	105(a)	35(abcde)	1260(a)
	2	31	5.3	21	4.5	85	25	124(a)	29(abcdef)	1702(a)
	3	79	12.7	39	3.2	97	7	84(a)	13(ef)	960(a)
	4	52	7.4	30.3	4	62	14	116(a)	40(abcd)	1489(a)

Table 3.6. Mean values of selected cotton, cover crop and weed parameters across different trial sites and treatments. Missing values in all cover crop species except lablab indicate that they were not tested at that site/ year. Lablab, tested as a marketable vegetable, was kept weed free, as was the control.

Treatment	Site	Biomass-fresh (tons ha^{-1})	Percent weed cover (%)	Height of cotton plants (cm)	No: of bolls (per plant)	Cotton yield (kg ha^{1})
Control	1	-	-	97	43	1378
	2	-	-	133	42	2267
	3	-	-	68	19	744
	4	-	-	109	43	1792
Lablab	1	-	-	150	50	1354
	2	-	-	126	19	2234
	3	-	-	68	15	481
	4	-	-	136	40	1420
Sesbania	1	17	38	101	36	1100
	2	19	37	122	26	2011
	3	59	7.4	64	17	627
	4	35	13	121	41	1803
Gliricidia	1	13	26	116	61	818
	2	-	-	-	-	-
	3	42	10	69	15	713
	4	10	21	127	42	1494
Sudan grass	1	19	55	66	19	1212
	2	13.5	59	124	33	1408
	3	39	28	63	12	456
	4	-	-	-	-	-

Table 3.6. Contd.

Treatment	Site	Biomass-fresh (tons ha^{-1})	Percent weed cover (%)	Height of cotton plants (cm)	No: of bolls (per plant)	Cotton yield (kg ha^{-1})
Mixture	1	-	-	-	-	-
	2	34	18	133	19	2665
	3	-	-	-	-	-
	4	50	15	107	42	1532
Sunnhemp	1	14	11	104	42	1532
	2	31	25	136	29	1832
	3	79	7	70	13	561
	4	52	14	141	42	1940

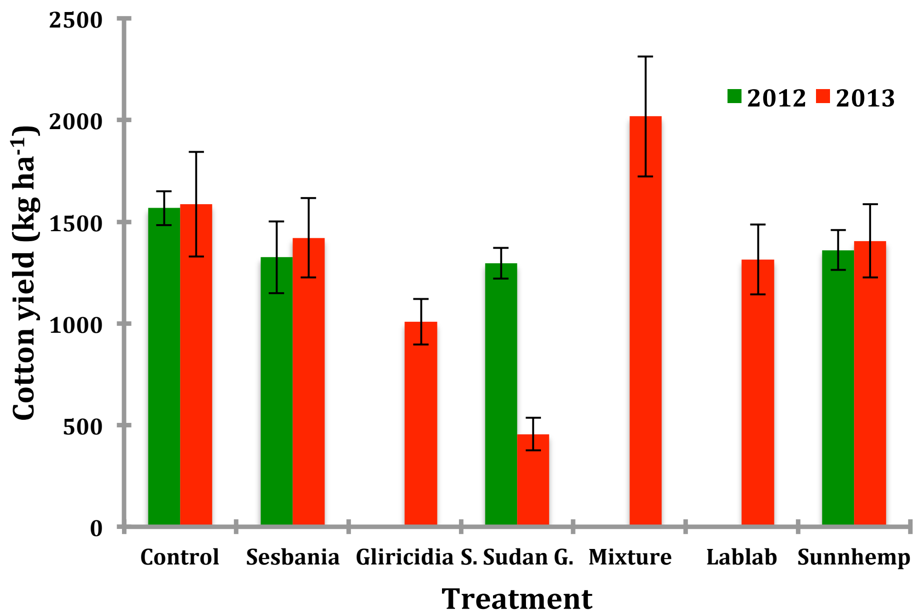

Fig. 3.1. Mean cotton yields (± SE) from the different treatments for each of the two trial years. Gliricidia, lablab and the mixture treatments were used only during the second year.

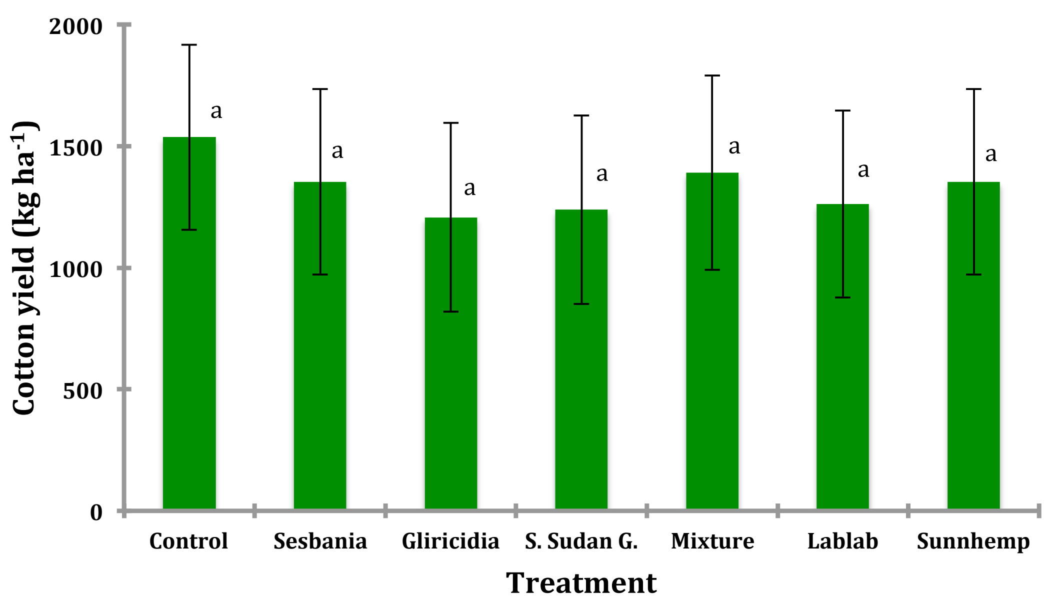

Fig. 3.2. Cotton yields (± SE) from the different cover crop treatments. Data from all four trial sites and both years were combined. Treatments connected by the same letter are not significantly different according to Tukey's test (α=0.05).

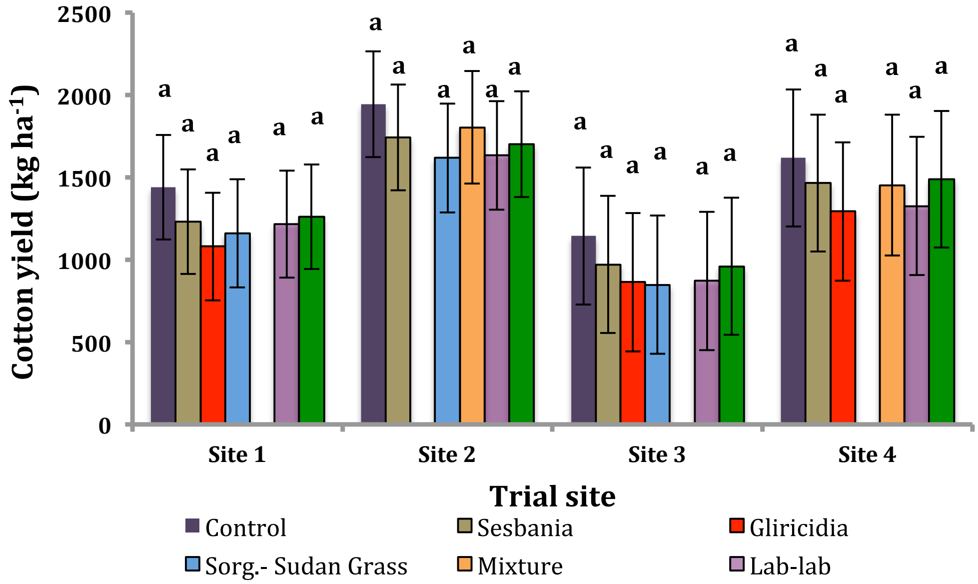

Fig. 3.3. Cotton yields (± SE) from the different treatments at each trial site. Data from all four trial sites and both years were combined. Missing bars indicate the treatments were not tested at those sites. Treatments connected by the same letter are not significantly different according to Tukey's test (α=0.05).

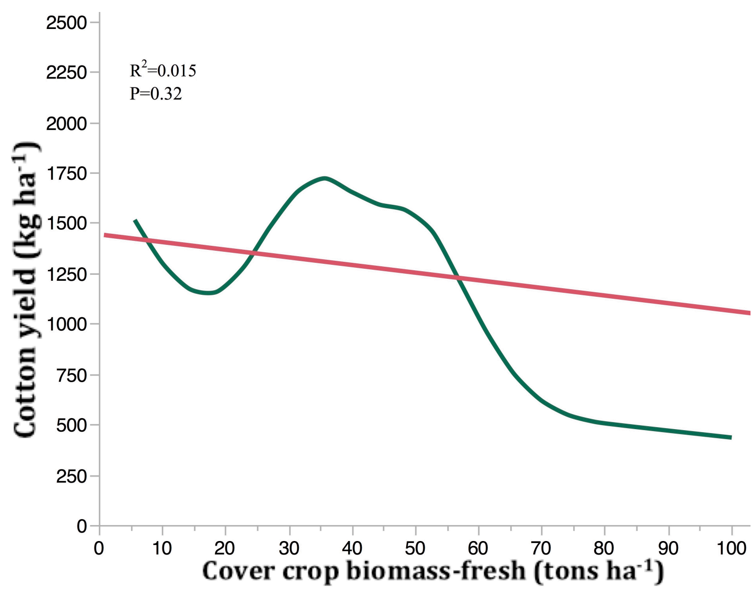

Fig. 3.4. Response of cotton yield to amount of cover crop biomass produced. Red (straight) line indicates the linear regression line of fit (α=0.05). Green line indicates a smooth line that follows the data trend at λ= 0.095. Data from all four trial sites and both years were combined.

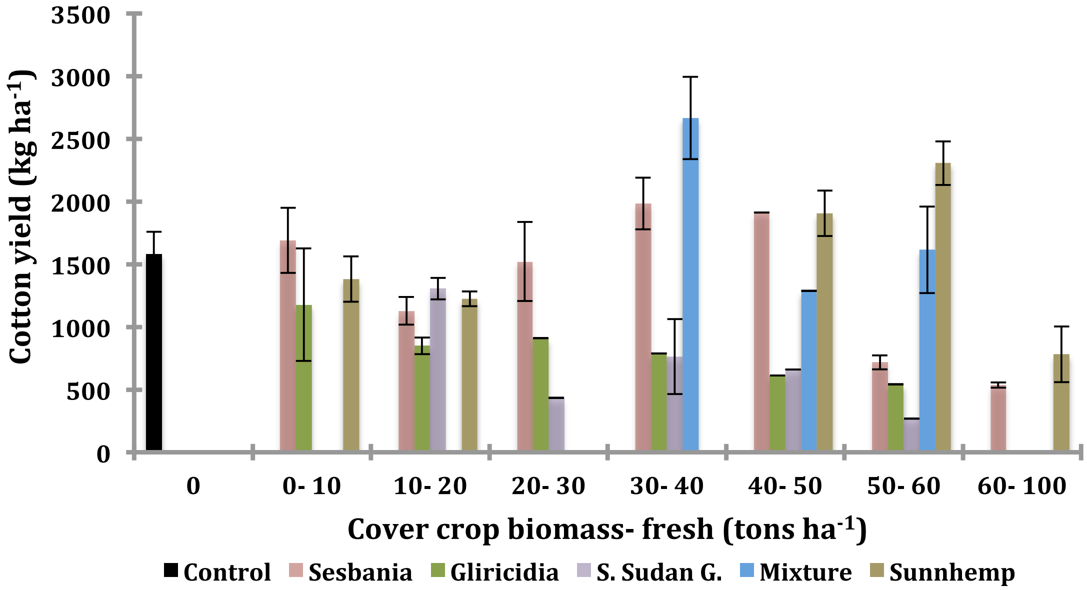

Fig. 3.5. Cotton yield (± SE) from different treatments at different levels of cover crop biomass production. Data from all four trial sites and both years were combined. Missing bars indicate biomass in that range was not produced by the cover crop treatment.

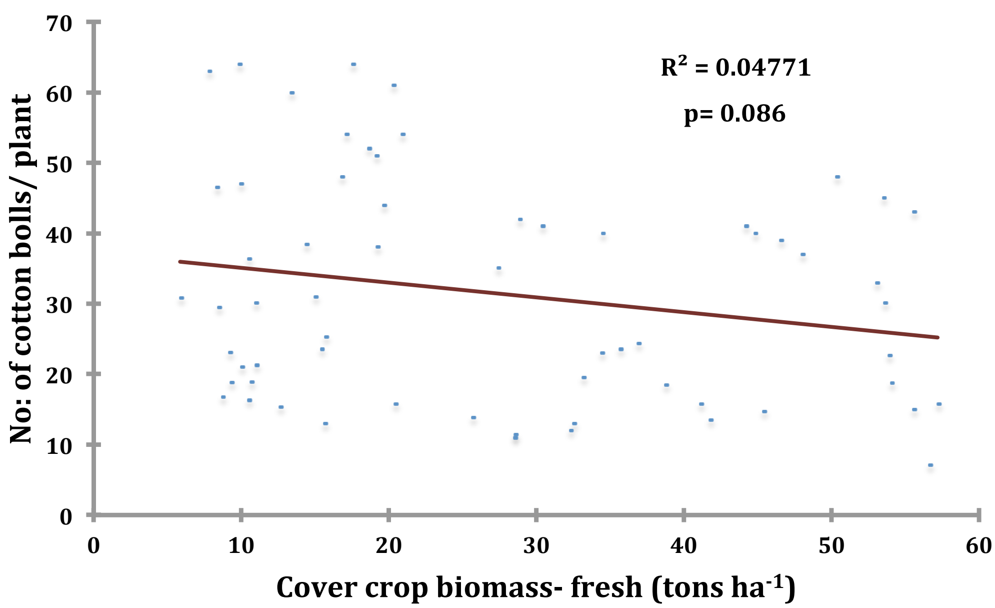

Fig. 3.6. Response (linear regression; α= 0.05) of the number of cotton bolls per plant to the amount of cover crop biomass produced. Data from all four trial sites and both years were combined.

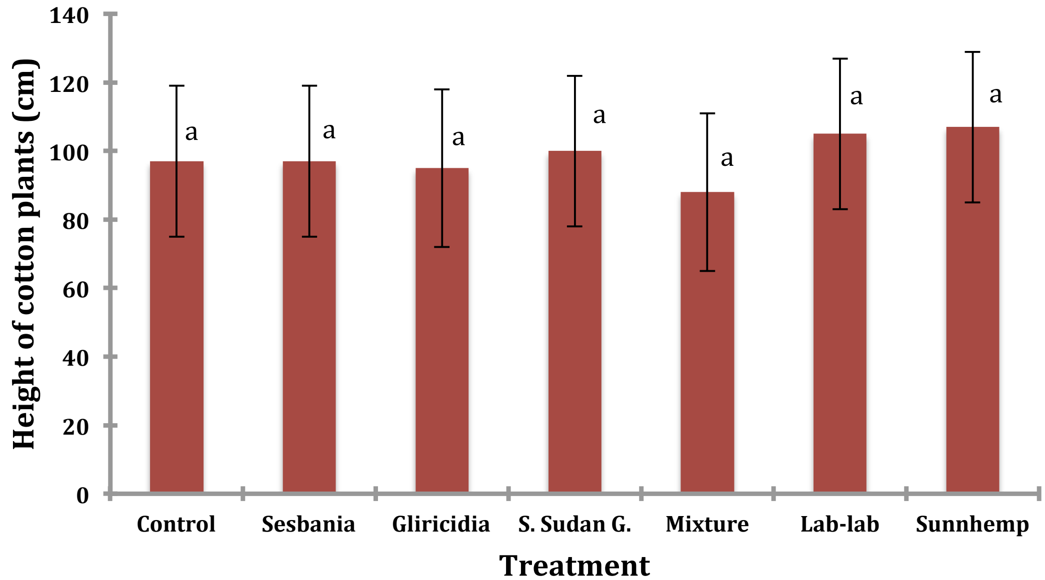

Fig. 3.7. Cotton plant height (± SE) at the different treatment plots. Data from all four trial sites and both years were combined. Treatments connected by the same letter are not significantly different according to Tukey's test (α=0.05).

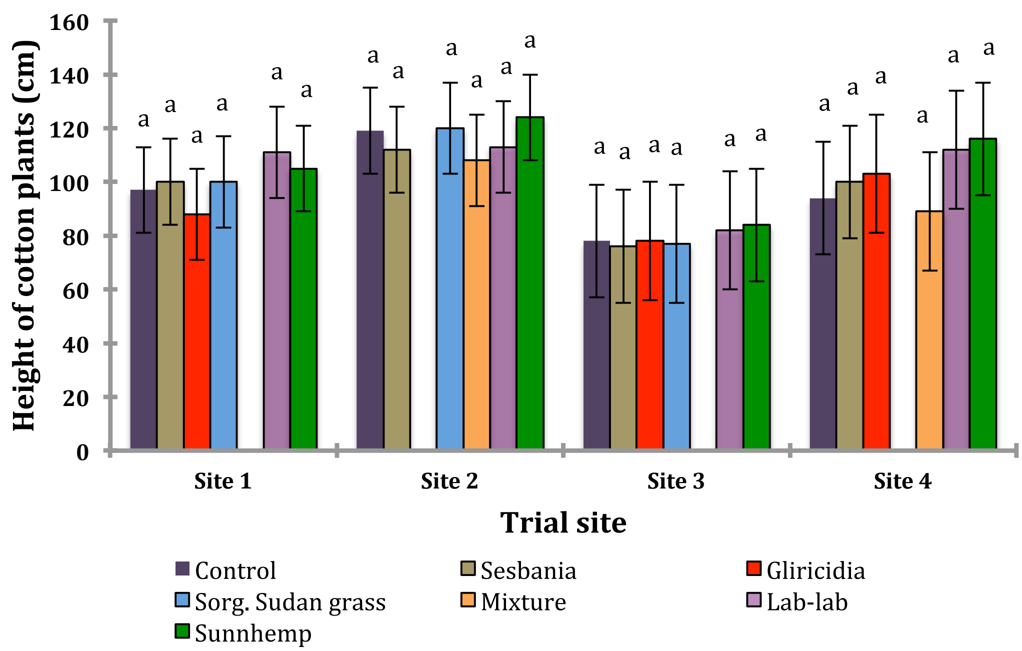

Fig. 3.8. Cotton plant heights (± SE) at the different treatments at each trial site. Data from all four trial sites and both years were combined. Missing bars indicate the treatments were not tested at those sites. Treatments connected by the same letter are not significantly different according to Tukey's test (α=0.05).

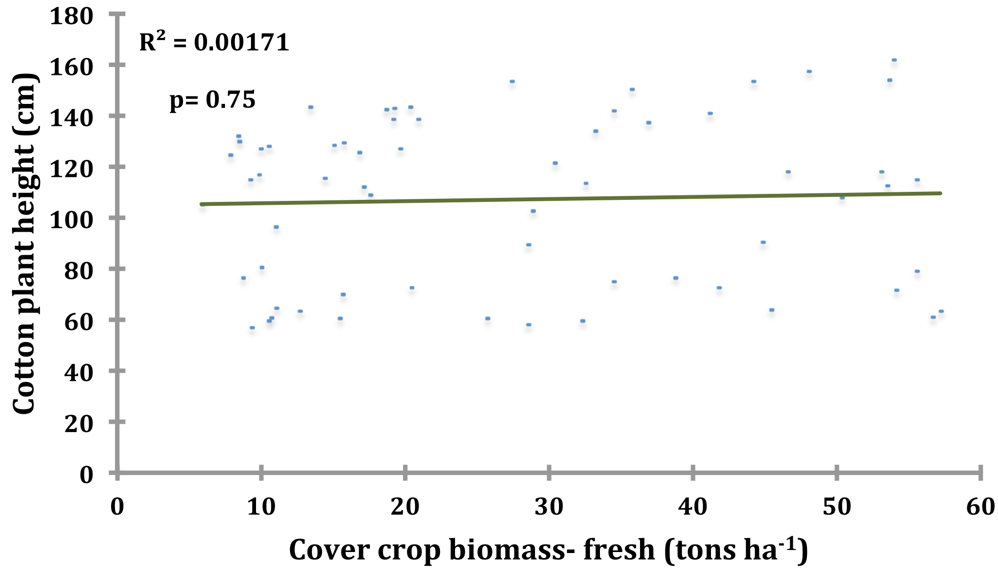

Fig. 3.9. Response (linear regression; α= 0.05) of cotton plant height to the amount of cover crop biomass produced. Data from all four trial sites and both years were combined.

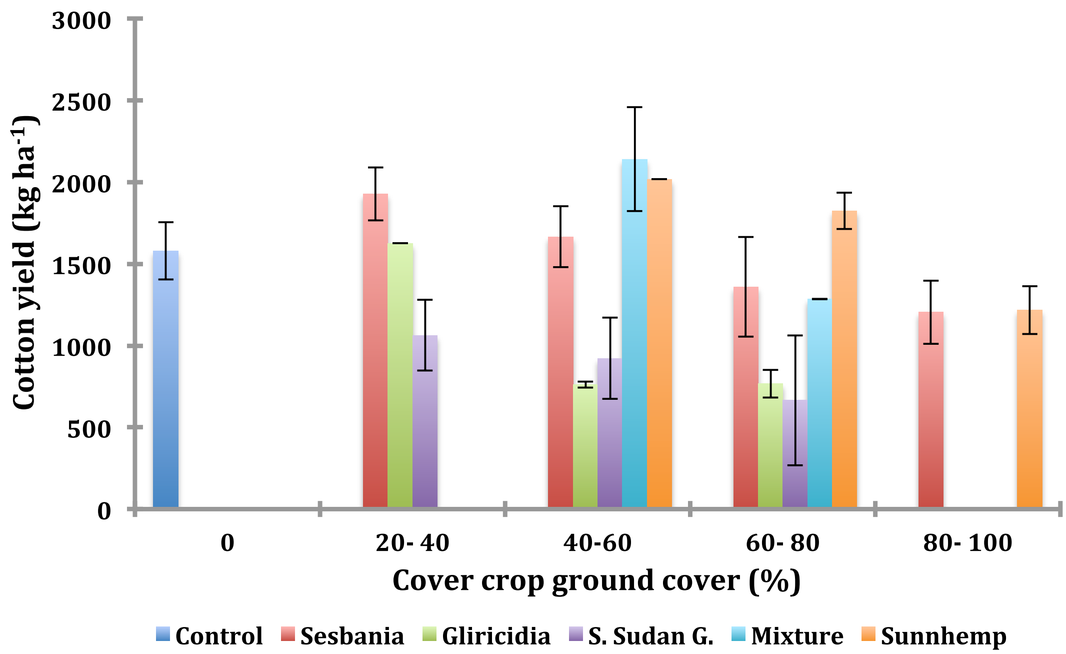

Fig. 3.10. Average cotton yields (± SE) from different cover crop treatments at different levels of cover crop ground cover. Data from all four trial sites and both years were combined. Missing bars indicate ground cover in that range was not produced by the cover crop treatment.

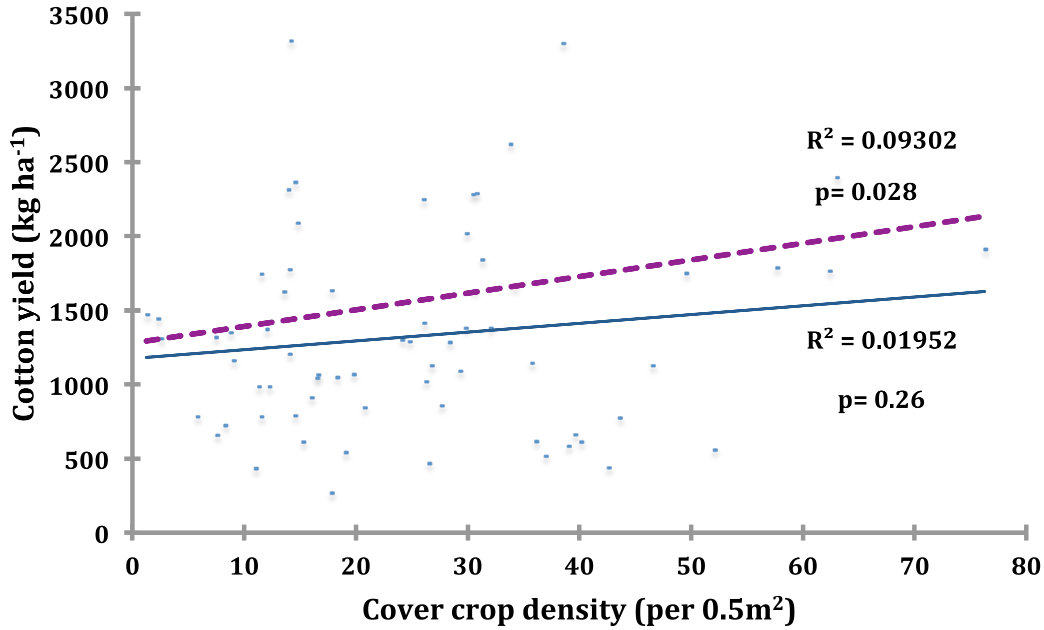

Fig. 3.11. Response (linear regression; α= 0.05) of cotton yield to density of cover crop stand. Data from all four trial sites and both years were combined. Solid line indicates data from all trial sites have been used; dotted line indicates that data from site 3 has been excluded.

Fig. 3.12. Water logging at Site 1, during the second year. Stagnation of water during the rainy months is a severe problem in the clayey vertisols of Vidarbha.

Fig. 3.13. Yellowing and stunting of cotton plants in sudan grass treatment plots at Site 3, during the second year.

Fig. 3.14. Cover crop seeds were not inoculated before planting; good nodulation was however observed in sesbania and sunnhemp at all trial sites.

CHAPTER 1V

Cover Crop Performance and Weed Suppression

Introduction

The experiment was conducted in the Vidarbha region of Maharashtra State, India. Referred to as the cotton belt of India, cotton and soybean are the predominant crops in this semi-arid area. The soils of this region are clayey vertisols that are very poor in organic matter. This depletion in soil organic matter is a combined result of intensive agriculture, hot tropical climate, farming practices that employ excessive tillage and removal of plant residue from the field every season for use as feed and fuel. During the hot and dry summer months, even weeds do not emerge and this leaves the soil surface exposed.

Growing cover crops is a way to increase the soil organic matter that is removed in the form of crop residue and through oxidation. Other benefits from a cover crop stand include cooler microclimate, weed suppression and, in the case of legume cover crops, possible decreases in nitrogen fertilization. For a cover crop to survive longer into the summer, establishment must be good. In order to achieve this level of root growth and sturdiness, they must be planted early in the growing season along with the cotton crop (early June) so that they benefit from the monsoon rains. Agriculture in Vidarbha is predominantly rainfed and planting cover crops after cotton harvest is not possible.

In cotton production here, herbicides are seldom used. For weed control, several inter-row cultivations using bullock driven hoes are carried out until the cotton canopy closes (Fig. 4.6). Cotton is slow growing during the first 2 to 3 months and can take up to 4 months to achieve full canopy size. Cotton is planted in late May or early June with the first rains. July and August are the rainiest months. So, in effect, most of the inter-row cultivations take place during the wettest months. Besides the labor involved, this destruction of soil structure by cultivating the clayey soils in their most intractable condition is another problem on account of these operations. The clayey vertisol soils in the region are also very difficult to work with (Burnett 1985) and timely weed management operations are not possible (Blaise and Ravindran 2003) (Fig. 4.7).

Hand weeding is also commonly carried out in the rows every few weeks to control the weeds that escape the inter-row cultivations. With the introduction of living mulches into the production system, this was the only weed control measure possible other than the weed suppressing abilities of the living mulches themselves and the mowing operations. Elimination of the frequent inter-row cultivations has many short and long term benefits. More labor, money and time can be saved and be diverted to other matters and physical properties of the soils can be enhanced.

Cotton, however, is a high value crop in the region and therefore, the weed suppressing capabilities of vigorously growing living mulches have to be evaluated before their promotion. Since the contributions to the sustainability functions of such an intercropped system is chiefly from the performance of the cover crops, their capacity for adequate biomass production and ground cover in this region have to be appraised.

Results and discussion

In order to understand the behavior of living mulch treatments and weeds at each trial site as well as to assess the broader effects across all the sites, the discussion in this chapter has been grouped into two sections. Observations from each site have been analyzed separately in Section 1. In Section 2, results from analyses of the collective data from all sites and both years have been presented. Through assessment of its performance across the different sites and years, feasibility for widespread adoption of each cover crop species can be understood.

Cover crop biomass production of more than 50 tons ha^{-1} were recorded in several treatment plots and biomass of up to 80 tons ha^{-1} was observed. Weed suppression by healthy cover crop stands was also effective. When cover crops had good emergence and low weed presence in the plots for the first 1 to 2 weeks of growth, weed densities were reduced to less than 15 plants m^{-2} in the absence of any other major weed control tactic. At crop harvest, cover crops that were cut back several times became susceptible to weed infestations since the regenerative capacity of these cover crops was reduced substantially. However, continuing the same mowing/cutting operations effectively managed the weeds in these treatment plots. Overall, the use of inter-seeded cover crops in these trials was as effective or, in some cases better than, conventional weed control methods in the region.

Section 1

Differences in farm management existed between the three on-farm trial sites and the site at the university research farm. The growers were asked not to change their farming practices and to manage the trial sites like the rest of their field, with the exception of the inter-row cultivation. Field conditions between the four sites were different in many respects because of these variations and produced somewhat dissimilar cover crop and weed behaviors. Cover crop and weed behaviors at each site have been examined separately in this section in order to understand the various possible outcomes of introducing living mulches into the cotton production system in Vidarbha. Statistical techniques and methods used were similar to the techniques described in Section 1, Chapter III. ANOVA was used to test for treatment effects and Tukey's HSD test was used to compare treatment differences. To investigate the relationships between cover crop and weed parameters, regression analyses were employed.

Site 1 Year 1

Cover crops produced, on average, 14 tons ha^{-1} of fresh biomass, with 69% ground cover. There was no significant difference between the treatments in terms of biomass production ($p= 0.24$; $R^2= 0.27$; Table 4.1). With 10 tons ha^{-1} biomass production, sunnhemp under-performed although ground cover (80%) was good. Sudan grass performed well and produced 19 tons ha^{-1} of fresh biomass. In two out of the 4 replications, more than 4 successful cuts were obtained in sudan grass treatments. There was a very steady increase in cover crop biomass from Replication 1 through Replication

4. This was likely because organic manure for the site was dumped across from Replication 4.

Treatments had a significant impact on the extent of ground cover ($p=0.046$; $R^2= 0.5$; Table 4.2). Results from Student's t test showed that sunnhemp (80%) achieved significantly higher ground cover than sudan grass (61%). Sudan grass had less than 60% cover in 2 replications. This was also, perhaps, because sudan grass tended to lose stand density quickly and result in tall thick-stemmed plants spaced widely apart. Cover crop density was also significantly different between the treatments ($p= 0.011$; $R^2= 0.63$; Table 4.3). Sudan grass had a significantly lower stand density than sesbania and sunnhemp.

Cover crop treatments had a significant effect on percent weed ground cover ($p= 0.0124$; $R^2= 0.75$; Table 4.4) or weed density ($p= 0.1$; $R^2= 0.64$; Table 4.5). Results from treatment comparisons showed that weed presence in sunnhemp (0.25%) was different from both sesbania and sudan grass. One of the reasons for this low weed presence in sunnhemp could be that it dried up suddenly enough that the last ground cover data recorded in these plots was when sunnhemp was at its peak growth.

There was a significant increase in weed ground cover with increase in cover crop biomass ($p= 0.0026$; $R^2= 0.61$). There was however, no change in weed density with cover crop biomass production ($p= 0.24$; $R^2= 0.14$). There was an overall decrease, albeit not significant, in weed ground cover with increase in cover crop ground cover ($p= 0.25$; $R^2= 0.13$).

Site 2 Year 1

There were no significant differences between the cover crop treatments with regard to amount of biomass ($p= 0.17$; $R^2= 0.28$; Table 4.1) but, in terms of ground cover, sunnhemp (78%) was significantly better than sudan grass (34%) (Table 4.2). All 3 cover crops were significantly different from each other in their stand densities (Table 4.3) with sesbania having the highest density of 14 plants $0.5m^{-2}$. Sudan grass had a density of only 2 plants $0.5m^{-2}$ but, like at Site 1, produced the most biomass. This, again, was because the poor densities resulted in tall, very thick-stemmed plants that had high masses individually; the cover although was very low with 34%. All replications were similar in regard to cover crop biomass, cover and density.

There was no significant effect of cover crop treatments on weed ground cover ($p= 0.37$; $R^2= 0.82$; Table 4.4). Student's t test also yielded no significant difference between the treatments. There were no significant correlations between weed ground cover and either cover crop biomass or ground cover. Although not statistically significant, weed ground cover in sunnhemp (38%) was much lower than in sesbania (58%) and sudan grass (59%) plots. Weed cover was more than 60% in plots with 0 to 10 tons ha^{-1} of cover crop biomass but only about 40% in those with 10 to 20 tons ha^{-1}. Similarly, in plots where cover crop ground cover was 20 to 80%, weed cover was approx. 70%, while it dropped to about 35% in cover crop plots with 80 to 100% ground cover.

Site 1 Year 2

Treatments were significantly different with regard to all cover crop parameters: biomass ($p= 0.037$; $R^2= 0.71$; Table 4.1), ground cover ($p= 0.0027$; $R^2= 0.5$; Table 4.2) and density ($p= 0.023$; $R^2= 0.82$; Table 4.3). Comparisons between the treatments showed that sesbania (20 tons ha^{-1}) produced significantly more biomass (fresh) than gliricidia (13 tons ha^{-1}) (Table 4.1). In terms of ground cover, both sesbania (83%) and sunnhemp (89%) were significantly greater than gliricidia (52%). Gliricidia had a significantly lower stand density than sunnhemp (Table 4.3). These considerable differences in ground cover and density could be due to the fact that gliricidia has a larger seed size and planting distance and very slow growth compared to the other species. Consequent establishment of gliricidia was also poor due to high weed presence.

Cover crops had no significant effect on weed ground cover ($p= 0.91$; $R^2= 0.02$; Table 4.4). Across the different treatments, mean weed cover was similar. Cover crop and weed parameters were uniform across the replications. Weeds exhibited no significant responses to cover crop biomass, cover or density. But, a negative trend (not statistically significant) was noticed with weed ground cover with increase in all of the three cover crop parameters. This suggests that, at this site, only the ground cover achieved by the cover crops and not their growth habit, influenced the extent of weed cover.

Site 2 Year 2

Cover crop treatments were significantly different in terms of biomass produced ($p= 0.015$; $R^2= 0.86$; Table 4.1) and extent of ground cover ($p= 0.002$; $R^2= 0.95$; Table 4.2). Sesbania showed significantly higher stand density than the mixture (Table 4.3). In terms of biomass produced, sunnhemp (50 tons ha^{-1}) was significantly higher than the mixture and sesbania (Table 4.1). All cover crops were significantly different from each other in their ground cover with sunnhemp (91%) having the most extensive cover; the mixture recorded only an average of 53% although biomass production was above par. Sesbania had a significantly higher density than the mixture (Table 4.3). Density and cover of the mixture treatment were not at par with sunnhemp or sesbania; this is probably because the sudan grass seeds in the mixture failed to emerge and gliricidia was extremely slow growing, more so than in its other test plots because it was continually shaded by the more aggressive sunnhemp and sesbania. The replications were uniform in their cover crop parameters.

Cover crop treatments had no significant effect on weed ground cover ($p=0.47$; $R^2= 0.18$; Table 4.4) or weed density ($p=0.33$; $R^2= 0.74$; Table 4.5). And none of the cover crops were significantly different in their weed parameters. Again, there was uniformity in the weed behavior between different replications. No significant response was found for weed ground cover with amount of cover crop biomass.

Site 3

Cover crop performance and weed suppression at Site 3 was excellent. High biomass production, extensive ground cover and healthy stand densities were observed. The cover crops regenerated well, which resulted in multiple successful cuts and they lasted long through the season and into the dry months. Cover crop biomass ($p= 0.0074$; $R^2= 0.33$; Table 4.1), ground cover ($p= 0.0006$; $R^2= 0.65$; Table 4.2) and density ($p< 0.0001$; $R^2= 0.87$; Table 4.3) were all significantly different between treatments.

Sunnhemp (79 tons ha^{-1}) produced significantly more biomass than gliricidia (42 tons ha^{-1}) and sudan grass (39 tons ha^{-1}). This excellent performance was noticeable in the field, sunnhemp was dense, vigorous and exhibited rapid growth and regeneration.

Cover crop treatments differed significantly in their ground covers. Sunnhemp (97%) was significantly better than gliricidia (75%) and sudan grass (48%) (Table 4.2). Sudan grass was significantly different from all others. In terms of stand density, sesbania and sunnhemp were significantly higher than gliricidia and sudan grass (Table 4.3). Sudan grass showed a healthy stand initially but dried up sooner than other cover crops leading to severe weed presence in the plots later in the season. Regeneration capacity was also lost quickly and sudan grass stands became more erratic with each mowing. Gliricidia was slow in its growth and cover but became vigorous during the latter part of the season and produced considerable biomass. It also outlasted all other cover crops and survived well into the hot and dry months up to early March.

Treatments had a significant effect on the extent of weed ground cover ($p = 0.002$; $R^2 = 0.78$; Table 4.4) but they did not have any effect on weed density ($p = 0.103$; $R^2 = 0.18$; Table 4.5). Sudan grass (28%) had a significantly higher weed cover than the other treatments. Weed density in sudan grass plots was also significantly higher than that in sunnhemp and gliricidia (Table 4.5). Weed density had no significant response to cover crop biomass, cover or density but, weed ground cover significantly dropped with increase in cover crop ground cover ($p = 0.0005$; $R^2 = 0.6$) and cover crop density ($p = 0.018$; $R^2 = 0.34$) (Fig. 11- appendix).

Site 4

Weed suppression by the cover crop treatments at this site was only next to Site 3. Cover crop performance in terms of biomass production and ground cover were also excellent; the stands were rapid in establishment, healthy and exhibited good regrowth. Cover crop treatments differed significantly in terms of the amount of their biomass production ($p= 0.0015$; $R^2= 0.9$; Table 4.1) and stand density ($p= 0.0005$; $R^2= 0.93$; Table 4.3). However, they had no effect on the extent of ground cover ($p= 0.052$; $R^2= 0.8$; Table 4.4). Between-treatment comparisons showed that sunnhemp and the mixture produced significantly more biomass than sesbania or gliricidia and both sesbania and gliricidia were significantly different from all other treatments (Table 4.1). Gliricidia had the lowest biomass with only 7.5 tons ha^{-1}.

Cover crop cover in gliricidia plots (33%) was also significantly lower than the other treatments (Table 4.2), which all had similar extent of cover. With regard to density, sesbania had a significantly denser stand than all other treatments (Table 4.3). Cover crop behavior across the different replications were uniform.

Cover crop species had no effect on extent of weed cover ($p= 0.94$; $R^2= 0.013$; Table 4.4) or density ($p= 0.28$; $R^2= 0.24$; Table 4.5). The treatments were also not significantly different (but were similar) in terms of their weed suppression. No significant trends were followed by weed ground cover or weed density to any of the cover crop parameters.

Section 2

Though intercropped, the cover crops produced considerable amounts of biomass at all trial sites. For ease of comparison, cover crop and weed parameter data (Table 3.5) have been presented graphically both by treatment and by trial site (Fig. 4.1; Fig. 4.2). Overall, across all sites and years, good weed suppression was observed in plots with high cover crop biomass and ground cover. Relations between cover crop parameters (ground cover, density and biomass) did not follow a definite pattern and interactions with weeds were complex. Outbreak or suppression of weeds could not always be completely explained by a single cover crop parameter like biomass production or ground cover and field observations provided understanding in this regard. To better understand the outcomes of the intercropped system, the performance of the living mulch cover crops and their effectiveness in suppressing weeds are discussed separately.

Cover crop density, ground cover and biomass

In terms of these cover crop performance parameters, Site 3 in location and sunnhemp and sesbania among cover crop species were better than the rest (Fig. 4.1 and 4.2). As expected, it was observed that (1) quick emergence, (2) good percent of emergence leading to dense stands and (3) rapid initial growth leading to almost total ground cover within 25 to 35 days from planting, were required for the living mulches to have a long and healthy stand. An initial weed free period of about 2 to 3 weeks was also essential for vigorous and uniform establishment. On average, the cover crops produced between 8 to 79 tons ha^{-1} of fresh biomass corresponding to 1 to 13 tons ha^{-1} of dry matter (Table 3.6). Up to 100 tons ha^{-1} of fresh biomass was recorded in one of the replications at Site 3.

Sesbania, gliricidia and sorghum sudan grass produced similar amounts of biomass (Fig. 4.1). Even though biomass production in terms of fresh weight was low, gliricidia had the highest dry matter content of these three species because of its dense, semi-woody stem; at all sites, gliricidia had the lowest wet to dry biomass ratio (Fig. 4.4). Sesbania had a high stand density of 37 plants $0.5m^{-2}$ (averaged across all sites and both years) on account of its small seed size and excellent emergence. Stand density was low in gliricidia and sudan grass plots. In gliricidia, this was a result of larger seed size and plant-to-plant spacing. However, in sudan grass plots, this was due to poor emergence and patchy stands.

Cover crop and weed parameters in sesbania treatment plots did not have a predictable relationship. Sesbania had a unique habit, which was perhaps, responsible for this behavior (Fig. 4.1). The plants had wide and dense crowns but, below this top layer of extensive canopy, the lower levels were sparse. Consequently, when cut back, but for the surface mulch, the inter-row space remained largely uncovered until the regrowth covered the space again. Because (1) ground cover data was collected immediately prior to the mowing operation and (2) ground cover was satisfactory, albeit not taking into account the intervals for regrowth, the data presented in Fig. 4.1 is an accurate representation of what was observed in the field.

This growth habit allowed sesbania to cover the ground quickly early in the season (Table 4.6). Along with sunnhemp, it was consistently the first cover crop treatment to achieve complete cover. Sesbania exhibited good early vigor at all sites and produced good amounts of biomass almost every time. At Site 3 during the second year, sesbania produced 59 tons ha^{-1} of fresh biomass and had 85% ground cover. Across all sites, an average of 29 tons ha^{-1} of fresh biomass and 71% ground cover were recorded (Fig. 4.1).

Sorghum sudan grass was the most ineffectual of the cover crop species. Of the four times it was tested, it exhibited an acceptable stand only on two occasions (Site 1 during the 1st year and Site 3 during the 2nd year). Across the two years, mean stand density and ground cover were 42 plants m^{-2} and 49% respectively (Fig. 4.1). An average of 19 tons ha^{-1} of fresh biomass recorded at Site 2 during the 2nd year was from a small number of large plants. This biomass was obtained from a stand density of about 8 plants m^{-2}, corresponding to approximately 167g per plant and an average ground cover of only 34%.

Sudan grass stand was healthy at Site 3 (Table 3.5) (although associated yield losses in cotton were noticed in all replications) but erratic in 3 out of 4 replications at Site 1 during Year 1. Sudan grass was planted 3 times at Site 1 during the second year but failed to establish an acceptable stand; therefore, the treatment was removed from the experiment. Re-planting was also carried out at Site 2 during the 1st year. From time of planting (June), it took 65 to 75 days (early September) for sudan grass to achieve around 80% ground cover at Site 1, but only 20 to 30 days (late July) to achieve this degree of cover at Site 3 (Table 4.6). However, this stand persisted only for a short time; at both sites, the extent of cover became inconsequential as the stand was lost within 20 to 25 days of attaining 80% cover. Overall, sudan grass was unreliable in emergence and sporadic in its stand. As a grass species, good regenerative capacity was expected of sudan grass; an average of 2 to 3 successful cuts were realized both years. This was lower than expected; sunnhemp and sesbania exhibited better regrowth in most plots.

All cover crops, but for gliricidia, achieved more than 80% ground cover within 3 to 4 weeks from planting (Table 4.6). Gliricidia was an exception to this rapid growth at all sites. Ten to fifteen days were necessary for complete emergence and larger weeds were hand weeded for approximately 3 weeks to prevent stunting or mortality due to weed infestation. Gliricidia took 8 to 16 weeks from planting to attain 80% ground cover (Table 4.6); and this extent of cover was achieved only in 2 out of the 3 sites where it was tested. There was severe stunting at Site 4 with an average ground cover of only 21%. Gliricidia plants were large enough for the mowing operation only in one replication; there was rampant weed infestation in the other three replications (77% weed cover) by early October. Weeds in these 3 plots were cut back like the cover crops when they grew too tall; this and the within (cotton)-row hand weeding is, perhaps, the reason no decline in cotton yield was recorded in the gliricidia plots at Site 4.

During the active growth period of the living mulches, it was common for weeds to be controlled, to some extent, by the same mowing operation employed for intercrop control. In almost all cases, prostrate or short weeds beneath the cover crop canopy were absent. Taller weeds were observed more frequently in healthy intercrop stands. In shaded environments, weeds have been known to grow taller by extending their internodes (Sultan 2000; Schmitt 1997; Ballare et al. 1987; Brainard et al. 2005). It is therefore possible that the mowing operations helped to control weeds that escaped smothering through this mechanism. Shorter and more prostrate weeds were more prevalent in plots with weak cover crop stands.

Gliricidia was not cut back as many times as sesbania or sunnhemp; however, it was observed to have excellent regenerative capacity. During an impending mowing operation, it was typical (unless immediately detrimental to cotton) to wait a few days so that, to the extent possible, data collection, cover crop management and field observations were carried out in the different cover crops at the same time. Gliricidia was consistently the first species to put forth new shoots after being cut back. On more than one occasion, some of the other cover crops dried up after being cut back the second time. Often, the cover crop vigor was suppressed for several days. These signs of stress after being cut back were uncommon in gliricidia, probably because of its woody stem and good ability for regrowth.

Gliricidia produced an average of 4.7 tons ha^{-1} of dry matter. This was the highest among gliricidia, sesbania and sudan grass (Fig. 4.1). Gliricidia stands survived until March at Sites 1 and 3, which made it the treatment that survived the longest into the summer, 9 to 12 weeks more than any other treatment. However, weed suppression was not effective during the last several weeks. This long survival into the summer was most likely due to its deep root system. Gliricidia had the deepest roots of all the cover crop species. At about 80 days from planting, the taproots reached a length of at least 70 to 80 cm. Measurements could not be made accurately beyond this period on account of breakage.

Sunnhemp was the most consistent in performance; at all trial sites and both the years, stands were good and biomass production was substantial (Table 3.5; Fig. 4.1). Average stand density in sunnhemp plots was 108 m^{-2} and was lower than 148 m^{-2} for sesbania. Ground cover for sunnhemp, however, was 82% over 71% for sesbania. This disparity is perhaps small but, sunnhemp maintained a much more steady cover (1) that did not decrease as drastically as sesbania upon each mowing operation and (2) for a longer duration. Extent of ground cover achieved by sunnhemp was greater than the mixture treatment (54%), which had the highest average biomass production among all treatments. Cover crop canopy in sunnhemp plots was, unlike sesbania, equally dense at all levels. Mowing operations (with either a weed whacker or a pair of shears) was most convenient in sunnhemp because of its non-branching and erect habit and because its foliage did not conceal the location of the main stem.

Most cover crop species reached their peak ground cover before the first mowing operation. From this point, the extent of cover decreased as the plants became less vigorous. However, at most trials during the second year, sunnhemp maintained good vigor and there was no decline in ground cover as the growing season progressed. On average, in these trials, sunnhemp stands sustained 87% ground cover even being cut back 3 times. There was however, a small decrease in cover crop density after every mowing operation. This was noticed in all treatments and was expected. The reason this did not lead to loss of ground cover is probably due to branching from the nodes right below the cut. Typically, 2 to 3 new branches were observed and they occupied gaps that resulted from sampling and aforementioned losses from plants drying up after being cut back. At Site 3, sesbania and gliricidia exhibited decreases in extent of ground cover, but only after they were cut back 2 to 3 times.

The mixture treatment produced an average of 43 tons ha^{-1} and 6.7 tons ha^{-1} of fresh and dry matter respectively. The dry biomass production was the highest among all treatments (Fig. 4.1). Interestingly, during the 2nd year, fresh to dry biomass ratio of 6 for sunnhemp, was lower than 6.5 for the mixture. Among the different species, gliricidia had the lowest ratio (5.4) (Fig. 4.4). It was expected that this characteristic of gliricidia would lower the ratio in the mixture treatment plots. To understand this, cover crop density was studied against the ratio of wet to dry biomass (Fig. 3- appendix). Overall, the ratio showed a significant positive response to cover crop density ($p= 0.0002$). In the field, plants in sparse stands were observed to grow woodier and vice versa, so, this was expected. However, when the treatments were individually plotted on a graph (Fig. 5- appendix), sudan grass and sunnhemp did not follow this trend. Sudan grass, under low densities, tended to grow large, succulent stems, which increased the fresh to dry matter ratio. The slight negative response in sunnhemp was likely due to its fibrous stem. This could explain the higher ratio for the mixture when compared to sunnhemp.

Separate measurements to assess the contributions of individual species in the mixture were not made. Sudan grass did not establish satisfactorily in any of the mixture treatment plots; so, its effects were absent in the outcomes. Cover crop stand densities in the mixture treatment were lower than sesbania and sunnhemp and higher than gliricidia and sudan grass. This was predicted because seed size of the different species in ascending order was sesbania> sunnhemp> sudan grass> gliricidia. Incongruence in sudan grass (Fig. 4.1) in view of the above discussion resulted from poor emergence and patchy stands. Lack of emergence of sudan grass in the mixture was also instrumental in the loss in stand density in this treatment. Another contributing factor was slow growth of gliricidia. These features of the mixture treatment were likely responsible for its lower stand densities and ground cover even though biomass production was good. Since gliricidia was slow growing and sudan grass did not emerge, initial mowing operations in the mixture treatment plots resulted in increased ground exposure.

The four trial sites showed varying degrees of cover crop performance and biomass production (Fig. 4.2). Cover crop dry matter production at Site 3 (9 tons ha^{-1}) was more than that at the other sites by a large margin. Fresh biomass production was in the order Site 3 (55 tons ha^{-1})> Site 4 (43 tons ha^{-1})> Site 2 (25 tons ha^{-1})> Site 1 (16 tons ha^{-1}). Cover crop stand density at Site 1 was similar to that at Site 2; the density at Site 4 was higher than that at Site 3. Biomass production at Site 1 was much lower than that at Sites 2 or 4, but ground cover at Site 1 was higher than that at Site 2 and comparable to Site 3. There was an overall increase in cover crop ground cover with cover crop stand density (Fig. 4- appendix). However, at Site 1, good cover crop cover was achieved with relatively lower stand density. This was likely because of several instances where cover crops at Site 1 dried up soon after the first or second mowing operation and ground cover data (collected before the mowing operation) was, therefore, not collected again, thus resulting in only high-value ground cover measurements for these plots. Hence, in these instances at Site 1, ground cover measurements were high values although duration of cover was short. At Site 2 and Site 4, cover crop regrowth was better than at Site 1, however, extent of ground cover gradually declined.

Cover crop parameters were exemplary at Site 3 where they performed as predicted. Every species attained good stands, cover and biomass production. Excellent regrowth (except in sudan grass) allowed the stands to remain healthy well into harvest time (November-December). Cover crop plants at Site 4 were also healthier and performed better than at Sites 1 and 2. Unlike at Site 3, cover crop stands at Site 4 were not robust in all replications and several plots began to dry up during the harvests. Amount of biomass produced by the different treatments were positively correlated to their stand densities (Fig. 4.3). Cover crop density at Site 1 was similar to that at Site 2 and Site 4, but it was higher than that at Site 3. Biomass production at Site 2 and Site 3, however, were more than at Site 1 and Site 4 respectively. This is probably because, beyond a certain stand density, biomass production depended on plant vigor, regenerative capacity and duration of the stand, all of which were better at Site 2 over Site 1 and at Site 3 over Site 4. The number of days required for the cover crops to attain more than 80% ground cover was similar across all sites (Table 4.6). The emergence percent/stand density however, varied. At the end of farm operations in late February, dried surface mulch in most of the sesbania, sunnhemp and mixture plots at Sites 2, 3 and 4 was enough to completely cover the soil surface and was several centimeters thick.

An important parameter that was studied with regard to cover crop biomass was the ratio of fresh to dry biomasses (Fig. 4.4). This measure of succulence could be significant in gaining a better understanding of competition for soil moisture, resistance to decomposition, etc. Succulence of the plants increases with increase in this ratio. On average, across all the sites, gliricidia was the least succulent with a ratio of 5.3 and sesbania was the most succulent with a 7.4 ratio. This woody nature of gliricidia was discernable in the field. The mixture treatment, sudan grass and sunnhemp had ratios of 6.6, 6.4 and 6.4 respectively. Succulence of sunnhemp was consistent across the different sites, whereas sesbania, sudan grass and the mixture displayed fluctuations.

There was a significant positive relationship between fresh to dry matter ratio and cover crop density ($p = 0.0002$; $R^2 = 0.18$; Fig. 3- appendix). This implies that when cover crop stands were erratic in plant density, the value of the ratio for that species became erratic too. This could be the reason for the fluctuations in the fresh to dry biomass ratios of sesbaina, sudan grass and mixture treatments. The positive correlation indicates further that, in denser stands, the cover crops were more succulent. This was corroborated by field observations: the cover crop plants tended to grow woodier when competition within the stand was low. Ground cover, however, was decreased by lower plant densities (Fig. 4- appendix).

Water availability was an important factor in cover crop succulence. Sites 1 and 3 had ratios of 6.1 and 6, respectively, while Sites 2 and 4 had ratios of 6.8 and 7.8, respectively. Site 1 was tested as a rainfed trial site and irrigated only under dire circumstances; Site 3 was irrigated but was not managed by the grower as well as Sites 2 and 4, which received irrigation every 1 to 2 weeks (rainfall data not shown but, all on-farm trials were within 4 to 6 kilometers of each other and received similar rainfall).

Treatments did not show any statistically significant correlations between amount of biomass produced and this ratio when averaged across the four sites (Fig. 12- appendix). Small trends were nevertheless observed. Gliricidia showed an increase in biomass production with increase in the fresh to dry biomass ratio. This suggests that plots with more succulent plants produced greater amounts of biomass. Sunnhemp showed an opposite trend. Sesbania, sudan grass and the mixture presented a slightly positive relationship with fresh biomass but a slightly negative trend when dry matter was plotted against this ratio. This indicates that (in these treatments) plots that yielded high amounts of fresh biomass were not necessarily the same ones that yielded high amounts of dry matter. In these cases, plots with more succulent plants yielded large amounts of fresh biomass but not dry biomass and vice versa. In view of the overarching goal of increasing the soil organic matter content, worthy of attention was the fact that fresh and dry biomasses were not as strongly correlated as expected.

Weed suppression

The intercropped cover crops did not affect cotton yields; this is indicative of adequate weed suppression by the cover crop treatments. Since no form of inter-row weed management was employed in the experiments, weed control was achieved primarily through the living mulches and the mowing operations. However, the effectiveness in weed control varied from one cover crop species to another. Average percent weed ground cover was in the order: sunnhemp (15%)< mixture (16%)< gliricidia (18%)< sesbania (28%)< sudan grass (46%) and average weed density was in the order: gliricidia (18 m^{-2})< mixture (19 m^{-2})< sunnhemp (27 m^{-2})< sesbania (30 m^{-2})< sudan grass (32 m^{-2}). There was a positive correlation between cover crop ground cover and cover crop density ($p= 0.014$; $R^2= 0.1$; Fig. 4- appendix) but, there was no relationship between weed cover and density ($p= 0.06$). Extent of weed cover was a better indicator of weed infestation than weed density because it considered weed size and presence of prostrate and spreading weeds better.

Weed ground cover decreased with increase in cover crop biomass (Fig. 5- appendix; Fig. 4.5; $p= 0.0002$; $R^2= 0.18$). There was also a negative correlation between weed ground cover and cover crop ground cover (Fig. 2- appendix; $p= 0.004$; $R^2= 0.11$). At all trial sites, weed presence in healthy intercrop stands was lowest early in the season, but increased as the season progressed. One reason for this could be the gradual loss in cover crop vigor. Similar observations by other researchers have also been attributed to nitrogen deficiency in the inter-row space due to rapid uptake by the cover crops, which selectively affects only weeds and not the crop (Seibert and Pearce 1993; Liebman and Davis 2000). In order to graphically represent the response of weed growth to cover crop growth in each individual treatment (Fig. 4.5), it was more prudent to use amounts of cover crop biomass rather than cover crop ground cover since the former better registered cover crop vigor, duration of stand and competitive ability. Sesbania, sunnhemp and the mixture showed quick emergence, growth and ground cover; early in the season, when they attained full cover, these treatments had less than 10% weed cover on average across the four sites (Table 4.6). Cover crop species that produced more biomass were also typically cut back more frequently because of their vigorous growth. This increased frequency of mowing and abundant surface mulch in these plots could perhaps have contributed to the reduction in weed presence, besides the direct smothering by the cover crop. Earlier studies (Graglia et al. 2006) have reported that weed biomass decreases rapidly with the frequency of mowing.

Weed presence in sesbania plots was relatively higher than in other treatments-except sudan grass (Fig. 4.1). The growth habit of sesbania plants, which was discussed previously, was perhaps, the cause. The sparseness (of foliage) in the bottom layers of the sesbania canopy could have facilitated the growth of weeds. Upon cutting back, the canopy opened up and the weeds could have capitalized on these 2 to 3 weeks of abundant sunlight before the cover crop closed canopy again. Rapid initial ground cover, however, suppressed weeds at all sites (Table 4.6). At Sites 1, 2 and 4, sesbania reduced the initial weed ground cover of 26% down to 8.6% at the time of first mowing. There was a decline in weed ground cover in sesbania plots with increase in biomass production (Fig. 4.5; $p= 0.0009$; $R^2= 0.43$). Average weed ground cover in sesbania dropped markedly and remained consistently lower as biomass production surpassed 20 tons ha^{-1} (Fig. 4.5).

Regenerative capacity of sesbania was not at par with sunnhemp or the mixture; in several plots, sesbania stands lost enough vigor after being cut back twice, that a third mowing became unnecessary and weed infestation was imminent. Succulent stems (Fig. 4.4) could have perhaps, hastened the dry-up. Exceptions to this situation were Site 2 and Site 3 during the second year where sesbania plots had an average of 86% ground cover after 3 cuttings (November) and showed good weed suppression (15%). Average weed densities at these sesbania plots were 21 m^{-2} and 16 m^{-2} at Site 2 and Site 3, respectively. Hence, despite the lack of a dense lower canopy, sesbania was capable of prolonged weed suppression in robust stands and the comparatively higher weed infestation in sesbania was also made conducive by its rather frequent short-duration stands.

Gliricidia was slow growing at all sites and showed poor weed suppression for 8 to 12 weeks before it achieved sufficient ground cover and canopy closure (Table 4.6). Mean cover crop density across all sites was 51 m^{-2}. Weed infestation was rampant during early stages of growth and plots at Site 1 had to be hand weeded at least once during the first month of planting. There was however, a negative correlation of gliricidia biomass production with weed ground cover (Fig. 4.5; $p= 0.02$; $R^2= 0.6$). Towards the end of October, approximately 4 months from planting, mean weed ground cover in gliricidia plots at Sites 1 and 3 was 13% and at Site 4, it was 71%.

At Site 3, where gliricidia stands were most robust and persistent, weed density was about 13 m^{-2}. After the initial slow growth phase, gliricidia developed dense, vigorous canopies, which smothered weeds effectively. As in sesbania, weed ground cover dropped substantially as biomass production (and associated vigor) crossed 20 tons ha^{-1} (Fig. 4.5). Gliricidia plots had the lowest mean weed density (18 m^{-2}) among all the treatments and weed ground cover was comparable to more vigorous treatments like sunnhemp and the mixture (Fig. 4.1; Fig. 4.5). Taking into account the elevated initial weed presence, this was likely because gliricidia peaked in vigor much later in the season (September to early October) when cotton growth and weed infestations were also at their peaks. Cotton growers in Vidarbha tend to grow cotton almost every year because it is a high value crop. Weed ecologists have long recognized that the life cycles of weeds associated with crops in such continuous cropping patterns are similar to the life cycles of the crops themselves (Brenchley and Warington 1933). So, mowing operations in gliricidia plots at this time also likely helped to control bulk of the weed population.

In terms of weed suppression, sorghum sudan grass was the least effective among the cover crop species. Highest mean weed density and weed ground cover were recorded in sudan grass plots (Fig. 4.1), 32 weeds m^{-2} and 46% respectively. Emergence was poor and in two out of the three occasions, sudan grass had to be re-sown. Erratic emergence led to patchy stands that resulted in the poor weed suppression. Due to the sparse and brief stands, there was no decrease in weed ground cover with increase in amount of sudan grass biomass (Fig. 4.5; $p= 0.62$; $R^2= 0.03$). Healthy stands were observed only at Site 3 where emergence was good and the stands were more competitive compared to the other treatments, albeit briefly because sudan grass plots started to deteriorate by

September. At Site 3, ground cover was achieved quickly (20 to 30 days from planting) with a stand density of 89 plants m^{-2}; weed ground cover and density were 28% and 17 m^{-2} respectively. During the first year, at Site 2, mean ground cover for sudan grass was recorded at 34%. Notwithstanding the fact that this was low, it was practically lower because mean cover crop density was 8 m^{-2}. The sudan grass plants were large and tall, but far from each other, which made any ground cover inconsequential because of the considerable interspace; weed ground cover here was about 60% by mid-August.

The mixture plots were only slightly higher in weed density than gliricidia (19 m^{-2}) and in weed ground cover than sunnhemp (16%) (Table 3.5). Sesbania and sunnhemp in the mixture covered the ground rapidly, and with onset of vigor in gliricidia, the mixture plots had dense cover crop foliage. There was a slight negative trend in weed ground cover with increase in biomass produced (Fig. 4.5), but it was not statistically significant ($p= 0.8$; $R^2= 0.02$). Emergence of sudan grass would have increased cover crop density; had this occurred, weed suppression could have, potentially, been lower because a combination of grasses and legumes suppress weeds better (Liebman and Dyck 1993). Sudan grass has been reported to decrease weed biomass by up to 89% (Brainard et al. 2011). Weed presence however, was low in most mixture treatment plots. Weed ground cover in mid-October at the beginning of cotton harvests was 20% at Site 2 and 32% at Site 4. At Site 4, mixture plots had the lowest degree of weed infestation among the different treatments. At Site 2, average weed ground cover and weed density were 16 m^{-2} and 18%; at Site 4, they were recorded at 22 weeds m^{-2} and 15% (Table 3.5).

The most consistent and effective treatment in weed suppression was sunnhemp. Among all treatments, sunnhemp had the lowest weed ground cover (15%) (Fig. 4.1). A decreasing trend was noticed in the response of weed ground cover to amount of sunnhemp biomass produced (Fig. 4.5); however, like in the mixture, this was not significant (p= 0.23; R^2= 0.07). This is likely because the weed presence in most sunnhemp plots were low throughout. Emergence was excellent at every site and on average, sunnhemp achieved more than 80% ground cover in 22 days of planting with only 8% weed cover (Table 4.6). Unlike in sesbania, growth habit of sunnhemp, with thick foliage at all levels of the cover crop canopy, maintained the inter-row ground cover upon being cut back. The cover crops dried up in October at Site 1 during the second year, resulting in inadequate weed suppression; at Sites 2, 3 and 4, weed cover at end of October was 10%, 8% and 34% respectively.

Average weed ground cover in the treatment plots during the second year dropped markedly to 16.3% from 43% during the first year. Experiments have reported increased weed seed mortality in reduced tillage systems due to high soil temperatures (Egley 1990). In a hot climate such as in Vidarbha, this could be one possible explanation for the decline in weed presence during the second year. Higher weed seed germinations have been reported from no tillage systems (Gallandt et al. 2004). Earlier experiments have also shown that primary tillage operations to stimulate weed seed emergence and subsequent mowing operations can hasten depletion of the weed seedbank (Gallandt et al. 2004; Gallandt 2006). Reduction in flowering and weed seed production, weed seed dormancies, inhibition of weed seed germination and smothering of weed seedlings have been reported from cover cropped systems (Smith and Whitelam 1997; Brainard and Bellinder 2004; Teasdale and Mohler 1993; Teasdale and Daughtry 1993; Teasdale and Mohler 2000). It was likely that this inter-row mowing, in association with the presence of living mulches, also controlled perennial weeds (which are usually hard to control in reduced tillage systems (Koskinen and McWhorter 1986)) because competition for light triggers greater allocation of assimilates to shoots rather than roots (Causin and Wulff 2003).

Current weed control practices in Vidarbha are centered on frequent inter-row hoeing operations. This utilizes a lot of labor and time. Because the majority of these operations occur during the rainy season, when the clayey soils are wet, they also result in destruction of soil structure. Reduced tillage goes hand-in-hand with living mulches and previous experiments in Vidarbha have shown potential for adoption of reduced tillage in cotton production (Blaise 2006). This project showed that intercropped cover crops in cotton production systems of Vidarbha can suppress weeds effectively and also produce copious amounts of biomass without interfering with the cotton crop.

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FIGURES AND TABLES

Table 4.1. Mean (LSD) cover crop biomass (fresh) (in tons ha^{-1}) from the different treatments at each trial site and year. Letters denoting significance and the standard error refer to values down each column. Treatments connected by the same letter are not significantly different according to Tukey's test (α=0.05).

Treatment	Cover crop biomass (tons ha^{-1})					
	Site 1 Year 1	Site 2 Year 1	Site 1 Year 2	Site 2 Year 2	Site 3	Site 4
Control	-	-	-	-	-	-
Sesbania	15(a)	8(a)	20(a)	31(b)	59(ab)	35(b)
Gliricidia	-	-	13(b)	-	42(b)	7.5(c)
Sudan grass	19(a)	14(a)	-	-	39(b)	-
Mixture	-	-	-	34(b)	-	50(a)
Lablab	-	-	-	-	-	-
Sunnhemp	10(a)	11.4(a)	17(ab)	50(a)	79(a)	52(a)
Std. error	3.4	1.6	1.7	3	6	3.4

Table 4.2. Mean (LSD) cover crop ground cover (%) from the different treatments at each trial site and year. Letters denoting significance and the standard error refer to values down each column. Treatments connected by the same letter are not significantly different according to Tukey's test (α=0.05).

Treatment	Cover crop cover (%)					
	Site 1 Year 1	Site 2 Year 1	Site 1 Year 2	Site 2 Year 2	Site 3	Site 4
Control	-	-	-	-	-	-
Sesbania	68(ab)	67(ab)	83(a)	70(b)	85(ab)	53(a)
Gliricidia	-	-	52(b)	-	75(b)	33(b)
Sudan grass	61(b)	34(b)	-	-	48(c)	-
Mixture	-	-	-	53(c)	-	55(a)
Lablab	-	-	-	-	-	-
Sunnhemp	80(a)	78(a)	89(a)	91(a)	97(a)	62(a)
Std. error	4.5	11	4	3.6	4.7	4.3

Table 4.3. Mean (LSD) cover crop stand density (per 0.5 m^2) from the different treatments at each trial site and year. Letters denoting significance and the standard error refer to values down each column. Treatments connected by the same letter are not significantly different according to Tukey's test (α=0.05).

Treatment	Cover crop stand density (per 0.5 m^2)					
	Site 1 Year 1	Site 2 Year 1	Site 1 Year 2	Site 2 Year 2	Site 3	Site 4
Control	-	-	-	-	-	-
Sesbania	31(a)	14(a)	15(ab)	42(a)	43(a)	61(a)
Gliricidia	-	-	9(b)	-	16(b)	14(b)
Sudan grass	12(b)	2(c)	-	-	16(b)	-
Mixture	-	-	-	14(b)	-	30(b)
Lablab	-	-	-	-	-	-
Sunnhemp	24(a)	11(b)	24(a)	32(ab)	39(a)	30(b)
Std. error	3.6	0.6	3	6.6	3	3.6

Table 4.4. Mean (LSD) weed ground cover (%) from the different treatments at each trial site and year. Letters denoting significance and the standard error refer to values down each column. Treatments connected by the same letter are not significantly different according to Tukey's test (α=0.05).

Treatment	Weed cover (%)					
	Site 1 Year 1	Site 2 Year 1	Site 1 Year 2	Site 2 Year 2	Site 3	Site 4
Control	-	-	-	-	-	-
Sesbania	52(a)	58(a)	25(a)	15(a)	7.4(b)	13(a)
Gliricidia	-	-	26(a)	-	10(b)	-
Sudan grass	55(a)	59(a)	-	-	28(a)	-
Mixture	-	-	-	18(a)	-	15(a)
Lablab	-	-	-	-	-	-
Sunnhemp	0.25(b)	38(a)	22(a)	11(a)	7(b)	14(a)
Std. error	11	19	6.5	4	3	3.6

Table 4.5. Mean (LSD) weed density (per 0.5 m^2) from the different treatments at each trial site and year. Letters denoting significance and the standard error refer to values down each column. Treatments connected by the same letter are not significantly different according to Tukey's test (α=0.05).

Treatment	Weed density (per 0.5 m^2)					
	Site 1 Year 1	Site 2 Year 1	Site 1 Year 2	Site 2 Year 2	Site 3	Site 4
Control	-	-	-	-	-	-
Sesbania	18(a)	-	-	5(a)	4(ab)	4.3(a)
Gliricidia	-	-	4.5(a)	-	3.2(b)	-
Sudan grass	11(b)	-	-	-	4.4(a)	-
Mixture	-	-	-	4(a)	-	5.4(a)
Lablab	-	-	-	-	-	-
Sunnhemp	14(ab)	-	7.8(a)	4.5(a)	3.2(b)	4(a)
Std. error	2.1	-	2.3	0.7	0.3	0.6

Table 4.6. Ground cover characteristics of the different cover crops species. Values of corresponding cover crop densities (per $0.5m^2$) are given in parentheses and corresponding weed cover (%) are given in square brackets. Missing values indicate the data was not collected. 'X' indicates that 80% cover was not attained.

Treatment	Site	Year	Date of cotton planting	Date of cover crop planting	No: of days (approx.) to attain more than 80% cover
Control	1	1	21-Jun	21-Jun	-
		2	12-Jun	17-Jun	-
	2	1	5-Jun	17-Jun	-
		2	6-Jun	20-Jun	-
	3	2	14-Jun	23-Jun	-
	4	2	3rd weed of May	6-Jul	-
Lablab	1	1	-	-	-
		2	12-Jun	17-Jun	-
	2	1	-	-	-
		2	6-Jun	20-Jun	-
	3	2	14-Jun	23-Jun	-
	4	2	3rd weed of May	6-Jul	-
Sesbania	1	1	21-Jun	21-Jun	25 to 40 (144) [33%]
		2	12-Jun	17-Jun	20 to 25 (-) [16%]
	2	1	5-Jun	17-Jun	-
		2	6-Jun	20-Jun	20 to 25 (190) [10%]
	3	2	14-Jun	23-Jun	20 to 25 (193) [8%]
	4	2	3rd weed of May	6-Jul	30 to 35 (308) [11%]
Gliricidia	1	1	-	-	-
		2	12-Jun	17-Jun	100 to 110 (37) [17%]
	2	1	-	-	-
		2	-	-	-
	3	2	14-Jun	23-Jun	60 to 70 (68) [11%]
	4	2	3rd weed of May	6-Jul	X

Table 4.6. Contd.

Treatment	Site	Year	Date of cotton planting	Date of cover crop planting	No: of days (approx.) to attain more than 80% cover
Sudan grass	1	1	21-Jun	21-Jun	-
		2	-	-	-
	2	1	5-Jun	17-Jun	60 to 75 (71) [55%]
		2	-	-	-
	3	2	14-Jun	23-Jun	20 to 30 (89) [8%]
	4	2	-	-	-
Mixture	1	1	-	-	-
		2	-	-	-
	2	1	-	-	-
		2	6-Jun	20-Jun	60 to 70 (91) [-]
	3	2	-	-	-
	4	2	3rd weed of May	6-Jul	30 to 35 (142) [<1%]
Sunnhemp	1	1	21-Jun	21-Jun	-
		2	12-Jun	17-Jun	23 to 28 (107) [8%]
	2	1	5-Jun	17-Jun	20 to 25 (96) [<1%]
		2	6-Jun	20-Jun	23 to 28 (133) [13%]
	3	2	14-Jun	23-Jun	20 to 25 (188) [3%]
	4	2	3rd weed of May	6-Jul	20 to 30 (221) [9%]

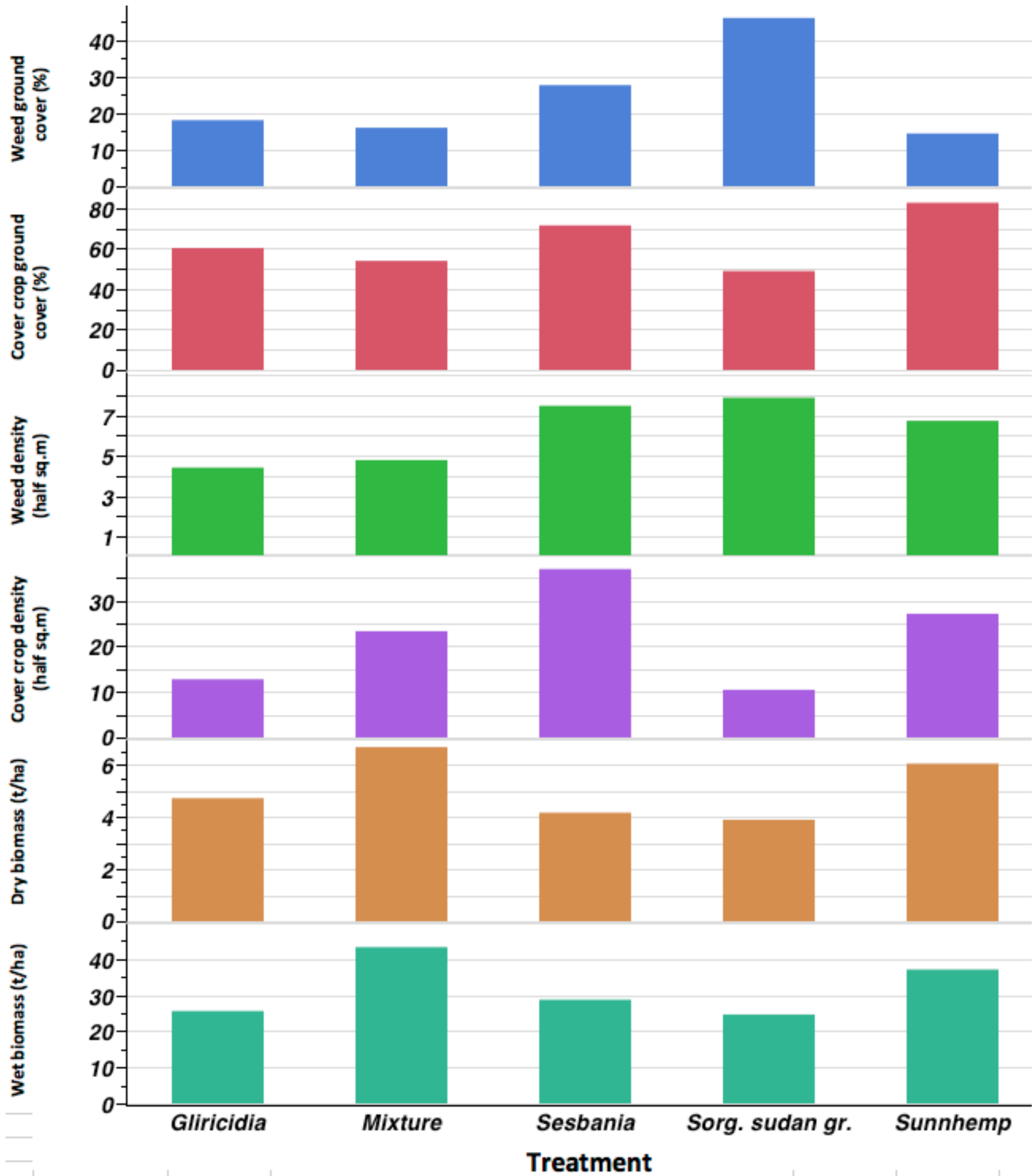


Fig. 4.1. Average cover crop and weed parameters for the different cover crop treatments. Data from all four trial sites and both years were combined.

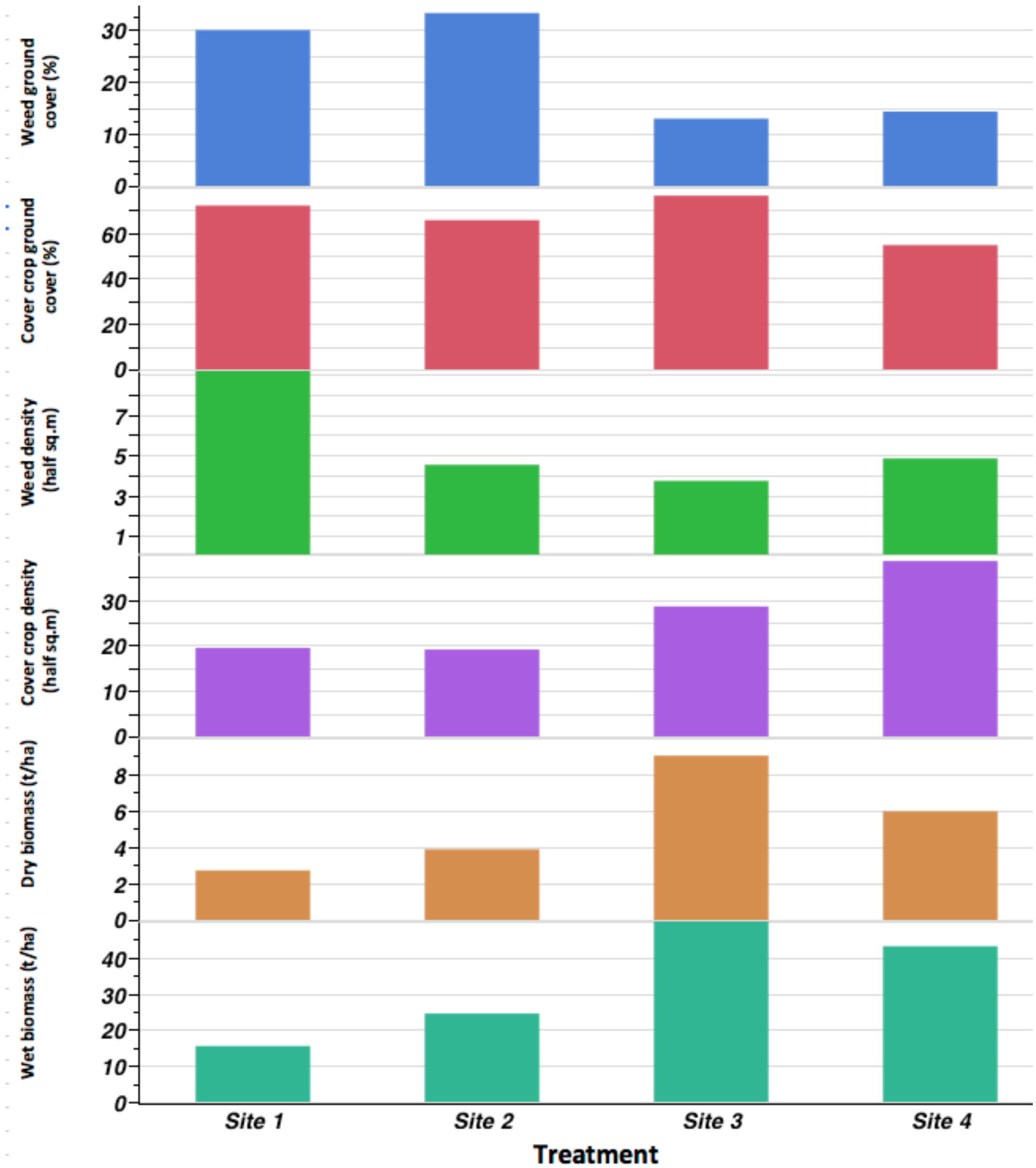


Fig. 4.2. Average cover crop and weed parameters for the different trial sites. Data from all four trial sites and both years were combined.

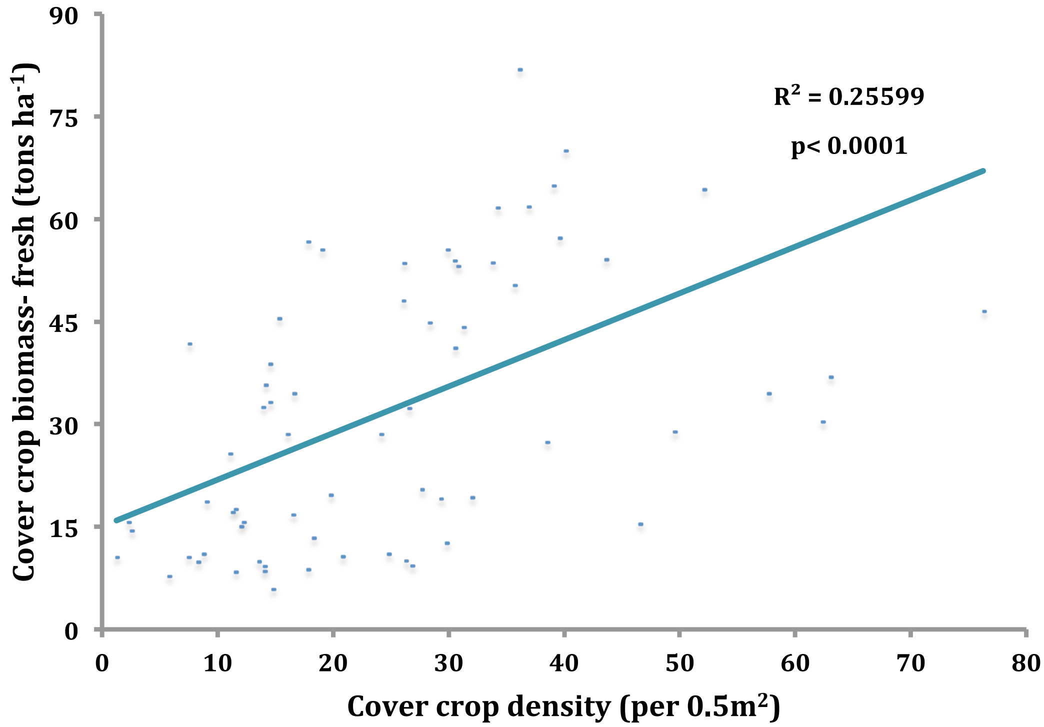


Fig. 4.3. Response (linear regression; α= 0.05) of the amount of cover crop biomass to the stand density. Data from all four trial sites and both years were combined.

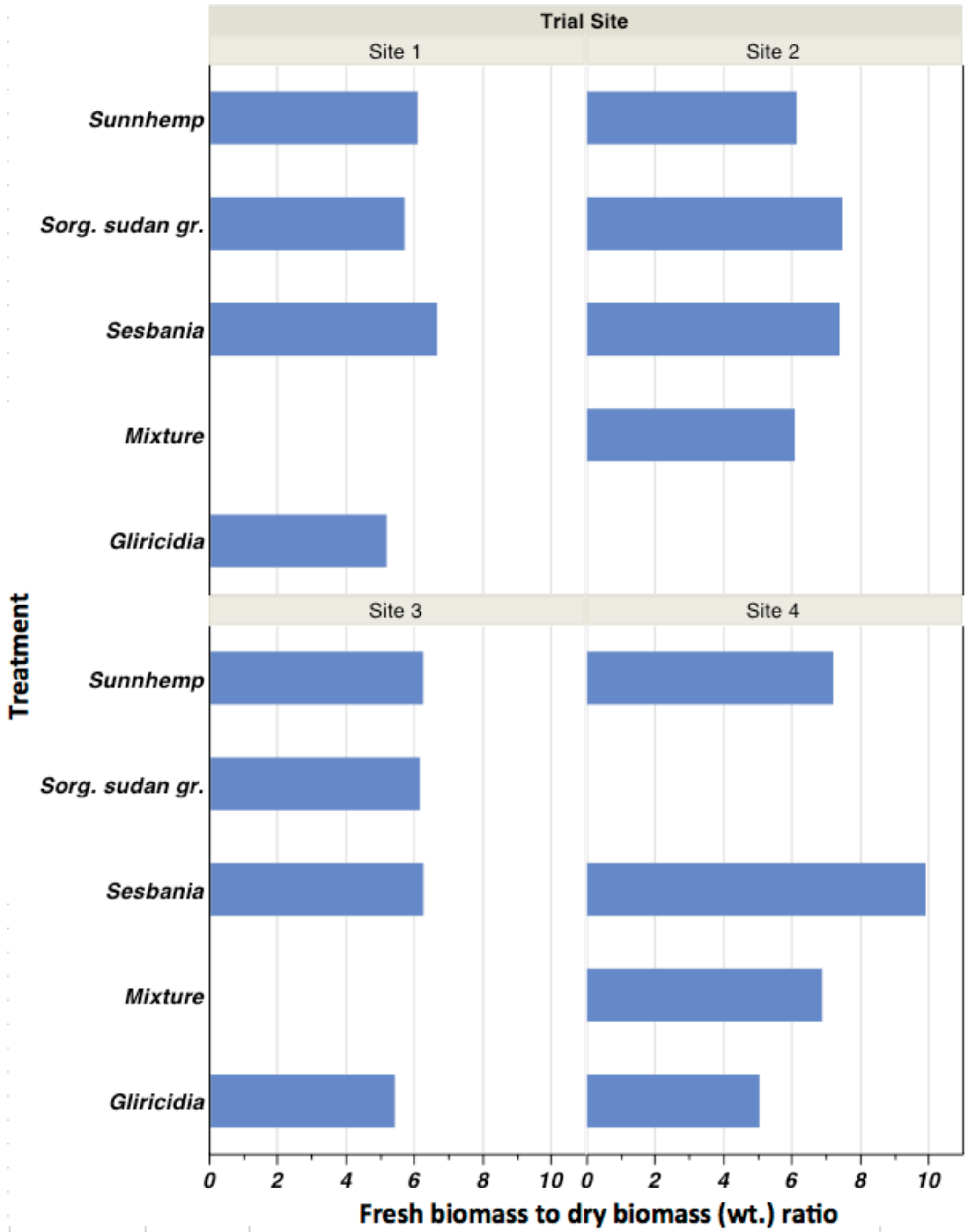


Fig. 4.4. Mean fresh to dry biomass ratio of the different cover crop species at each trial site. Data from all four trial sites and both years were combined. Missing bars indicate the treatments were not tested at those sites.

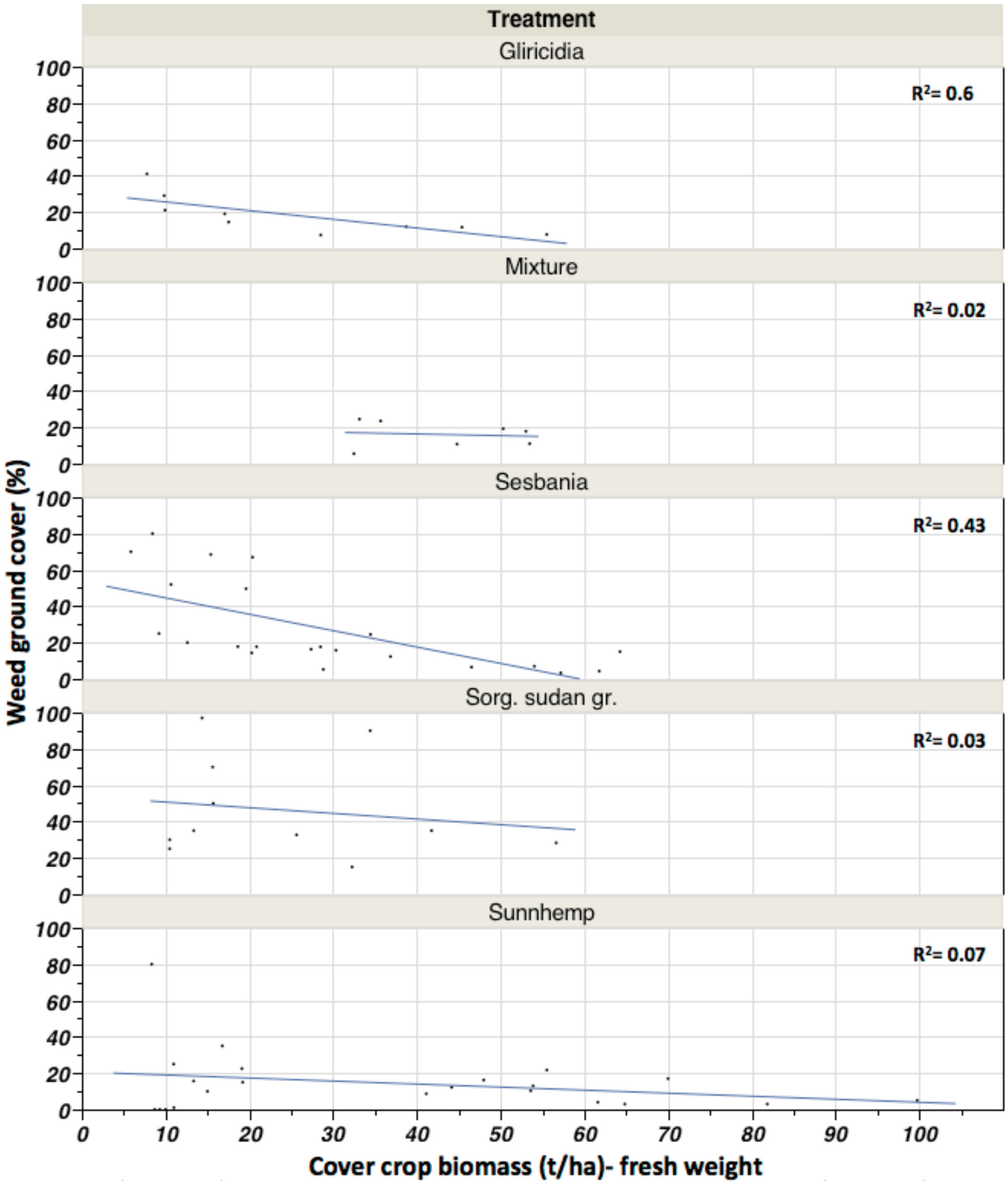


Fig. 4.5. Response (linear regression; α= 0.05) of the extent of weed cover to the amount of cover crop biomass produced. Data from all four trial sites and both years were combined.

Fig. 4.6. One of the bullock driven inter-row cultivation tools commonly used in cotton production systems in Vidarbha.

Fig. 4.7. Vertisol soils of Vidarbha, on which cotton is predominantly grown, are difficult to work with during the wet months, making timely farm operations difficult.

APPENDIX

Table 1. Mean cotton yield (in kg ha^{-1}) corresponding to the different levels of cover crop biomass production at each trial site and year. Letters denoting significance refer to values down each column. Treatments connected by the same letter are not significantly different according to Tukey's test (α=0.05). Lablab has been excluded since biomass was not recorded for this treatment. Blank cells indicate that the level of biomass was not recorded during that Site-Year.

Cover crop biomass-fresh (tons ha^{-1})	Cotton yield (kg ha^{-1})					
	Site 1 Year 1	Site 2 Year 1	Site 1 Year 2	Site 2 Year 2	Site 3	Site 4
0 (Control)	1492(a)	1666(a)	1264(a)	2867(a)	744(a)	1792(a)
0-10	1259(a)	1703(a)	725(a)	-	-	1626(a)
10-20	1203(a)	1388(a)	1033(a)	-	-	-
20-30	856(a)	-	1144(a)	2302(a)	671(a)	1748(a)
30-40	1064(a)	-	-	2598(a)	626(a)	1776(a)
40-50	-	-	-	1631(a)	635(a)	1820(a)
50-60	-	-	-	2449(a)	561(a)	1716(a)
60-100	-	-	-	-	553(a)	1659(a)

Table 2. Mean cotton plant height (in cm) corresponding to the different levels of cover crop biomass production at each trial site and year. Letters denoting significance refer to values down each column. Treatments connected by the same letter are not significantly different according to Tukey's test (α=0.05). Lablab has been excluded since biomass was not recorded for this treatment. Blank cells indicate that the level of biomass was not recorded during that Site-Year.

Cover crop biomass-fresh (tons ha^{-1})	Cotton plant height (cm)					
	Site 1 Year 1	Site 2 Year 1	Site 1 Year 2	Site 2 Year 2	Site 3	Site 4
0 (Control)	68(a)	121(a)	125(a)	145(a)	68(a)	109(a)
0-10	71(a)	121(a)	117(a)	-	-	127(a)
10-20	62(a)	120(a)	130(a)	-	-	-
20-30	73(a)	-	136(a)	122(a)	59(a)	103(a)
30-40	75(a)	-	-	134(a)	68(a)	132(a)
40-50	-	-	-	141(a)	68(a)	130(a)
50-60	-	-	-	158(a)	69(a)	113(a)
60-100	-	-	-	-	67(a)	137(a)

Table 3. Mean cotton boll count (per plant) corresponding to the different levels of cover crop biomass production at each trial site and year. Letters denoting significance and the standard error refer to values down each column. Treatments connected by the same letter are not significantly different according to Tukey's test (α=0.05). Lablab has been excluded since biomass was not recorded for this treatment. Blank cells indicate that the level of biomass was not recorded during that Site-Year.

Cover crop biomass-fresh (tons ha^{-1})	**Cotton boll count (per plant)**					
	Site 1 Year 1	**Site 2 Year 1**	**Site 1 Year 2**	**Site 2 Year 2**	**Site 3**	**Site 4**
0 (Control)	23(a)	42(a)	64(a)	42(a)	19(a)	43(a)
0-10	19(a)	33(a)	64(a)	-	-	47(a)
10-20	19(a)	32(a)	54(a)	-	-	-
20-30	16(a)	-	53(a)	23(a)	13(a)	42(a)
30-40	23(a)	-	-	20(a)	15(a)	41(a)
40-50	-	-	-	16(a)	14(a)	39(a)
50-60	-	-	-	26(a)	14(a)	42(a)
60-100	-	-	-	-	14(a)	46(a)

Table 4. Mean cotton yield (in kg ha^{-1}) corresponding to the different levels of cover crop ground cover at each trial site and year. Letters denoting significance refer to values down each column. Treatments connected by the same letter are not significantly different according to Tukey's test (α=0.05). Lablab has been excluded since ground cover data was not recorded for this treatment. Blank cells indicate that the level of ground cover was not recorded during that Site-Year.

Cover crop ground cover (%)	Cotton yield (kg ha^{-1})					
	Site 1 Year 1	Site 2 Year 1	Site 1 Year 2	Site 2 Year 2	Site 3	Site 4
0 (Control)	1492(a)	1666(a)	1265(a)	2867(a)	744(a)	1792(a)
0-20	-	-	-	-	-	-
20-40	-	1579(a)	-	-	545(a)	1696(a)
40-60	1151(a)	-	762(b)	2324(a)	464(a)	1760(a)
60-80	1198(a)	1746(a)	1027(ab)	3301(a)	613(a)	1755(a)
80-100	1144(a)	1424(a)	1154(a)	2232(a)	599(a)	-

Table 5. Mean cotton plant height (cm) corresponding to the different levels of cover crop ground cover at each trial site and year. Letters denoting significance refer to values down each column. Treatments connected by the same letter are not significantly different according to Tukey's test (α=0.05). Lablab has been excluded since ground cover data was not recorded for this treatment. Blank cells indicate that the level of ground cover was not recorded during that Site-Year.

Cover crop ground cover (%)	Cotton plant height (cm)					
	Site 1 Year 1	Site 2 Year 1	Site 1 Year 2	Site 2 Year 2	Site 3	Site 4
0 (Control)	68(a)	121(a)	125(b)	145(a)	68(a)	109(a)
0-20	-	-	-	-	-	-
20-40	-	120(a)	-	-	67(a)	124(a)
40-60	65(a)	-	117(b)	122(a)	60(a)	119(a)
60-80	67(a)	132(a)	120(b)	154(a)	67(a)	128(a)
80-100	67(a)	118(a)	139(a)	149(a)	68(a)	-

Table 6. Mean cotton boll count corresponding to the different levels of cover crop ground cover at each trial site and year. Letters denoting significance refer to values down each column. Treatments connected by the same letter are not significantly different according to Tukey's test (α=0.05). Lablab has been excluded since ground cover data was not recorded for this treatment. Blank cells indicate that the level of ground cover was not recorded during that Site-Year.

Cover crop ground cover (%)	No: of cotton bolls per plant					
	Site 1 Year 1	Site 2 Year 1	Site 1 Year 2	Site 2 Year 2	Site 3	Site 4
0 (Control)	23(a)	42(a)	64(a)	42(a)	19(a)	43(a)
0-20	-	-	-	-	-	-
20-40	-	33(a)	-	-	14(a)	44(a)
40-60	15(a)	-	64(ab)	17(a)	12(a)	41(a)
60-80	20(a)	47(a)	49(ab)	35(a)	14(a)	41(a)
80-100	20(a)	28(a)	52(b)	23(a)	14(a)	-

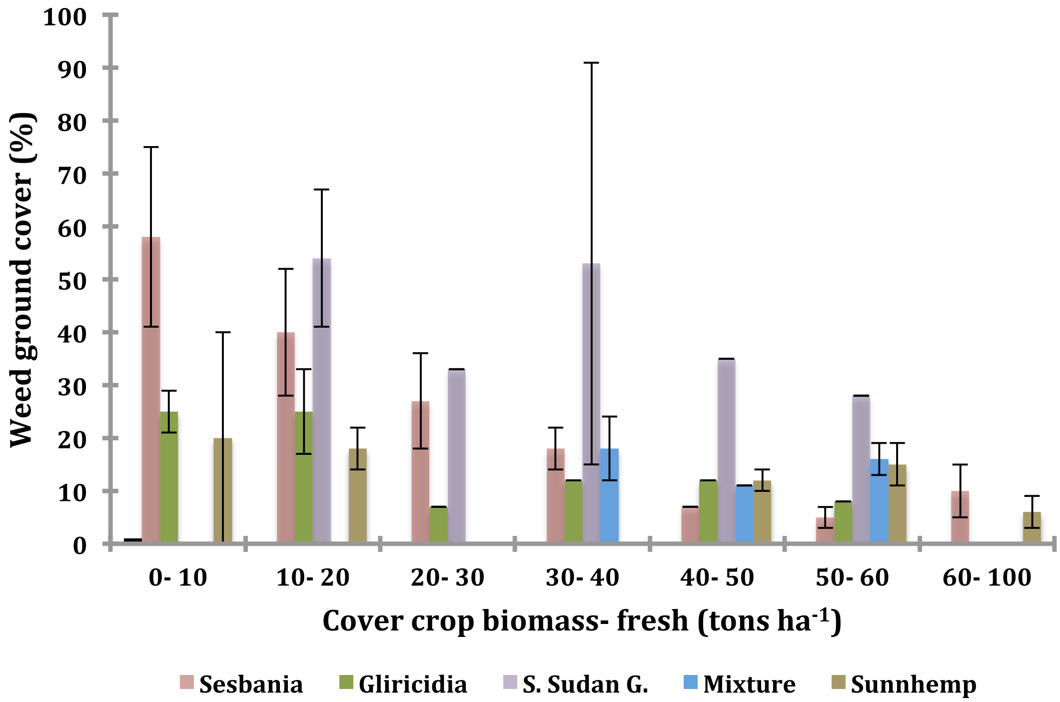


Fig. 1. Weed ground cover (± SE) in the different cover crop treatments at various levels of their biomass production. Data from all four trial sites and both years were combined. Missing bars indicate that biomass in that range was not produced by the treatment.

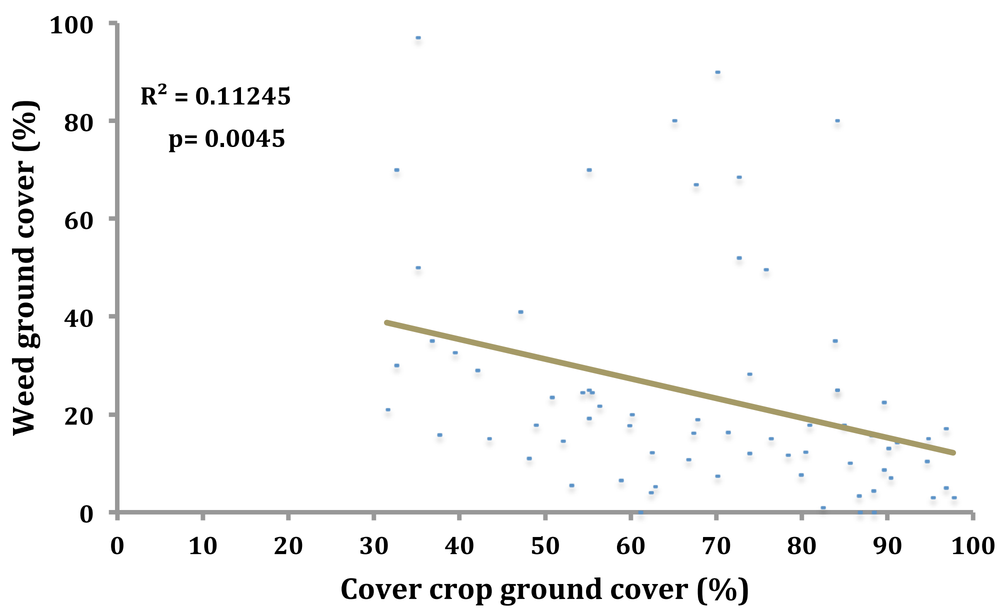


Fig. 2. Response (linear regression; α= 0.05) of weed ground cover to cover crop ground cover. Data from all four trial sites and both years were combined.

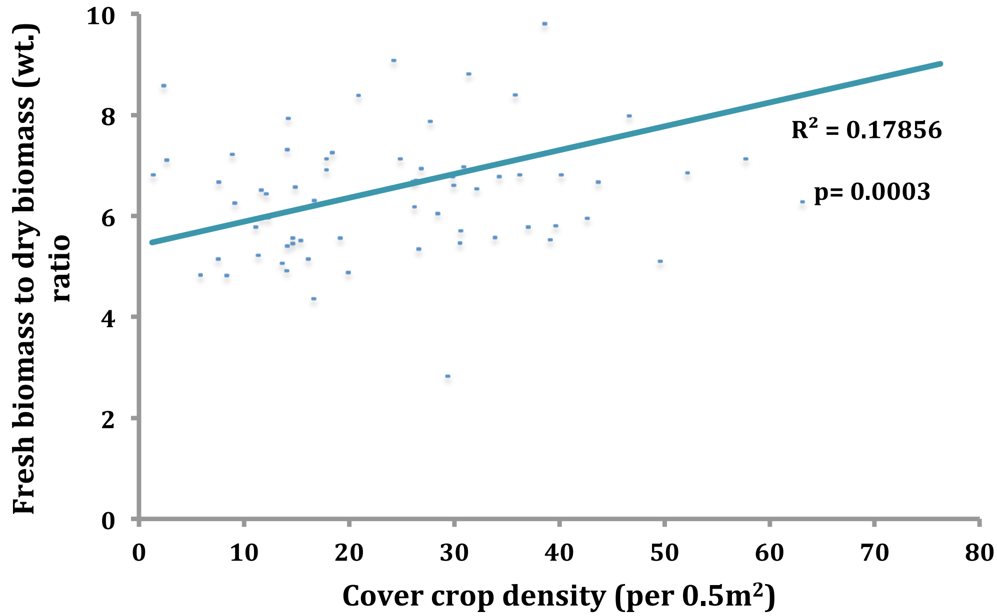


Fig. 3. Relationship (linear regression; α= 0.05) between ratio of fresh to dry cover crop biomass and stand density. Data from all four trial sites and both years were combined.

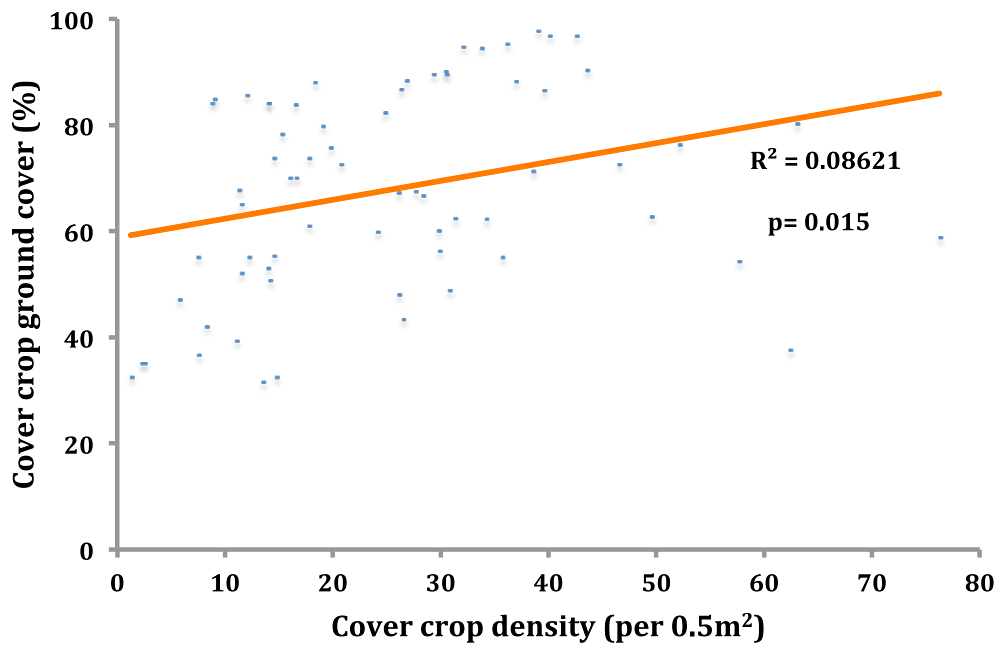


Fig. 4. Response (linear regression; α= 0.05) of cover crop ground cover to stand density. Data from all four trial sites and both years were combined.

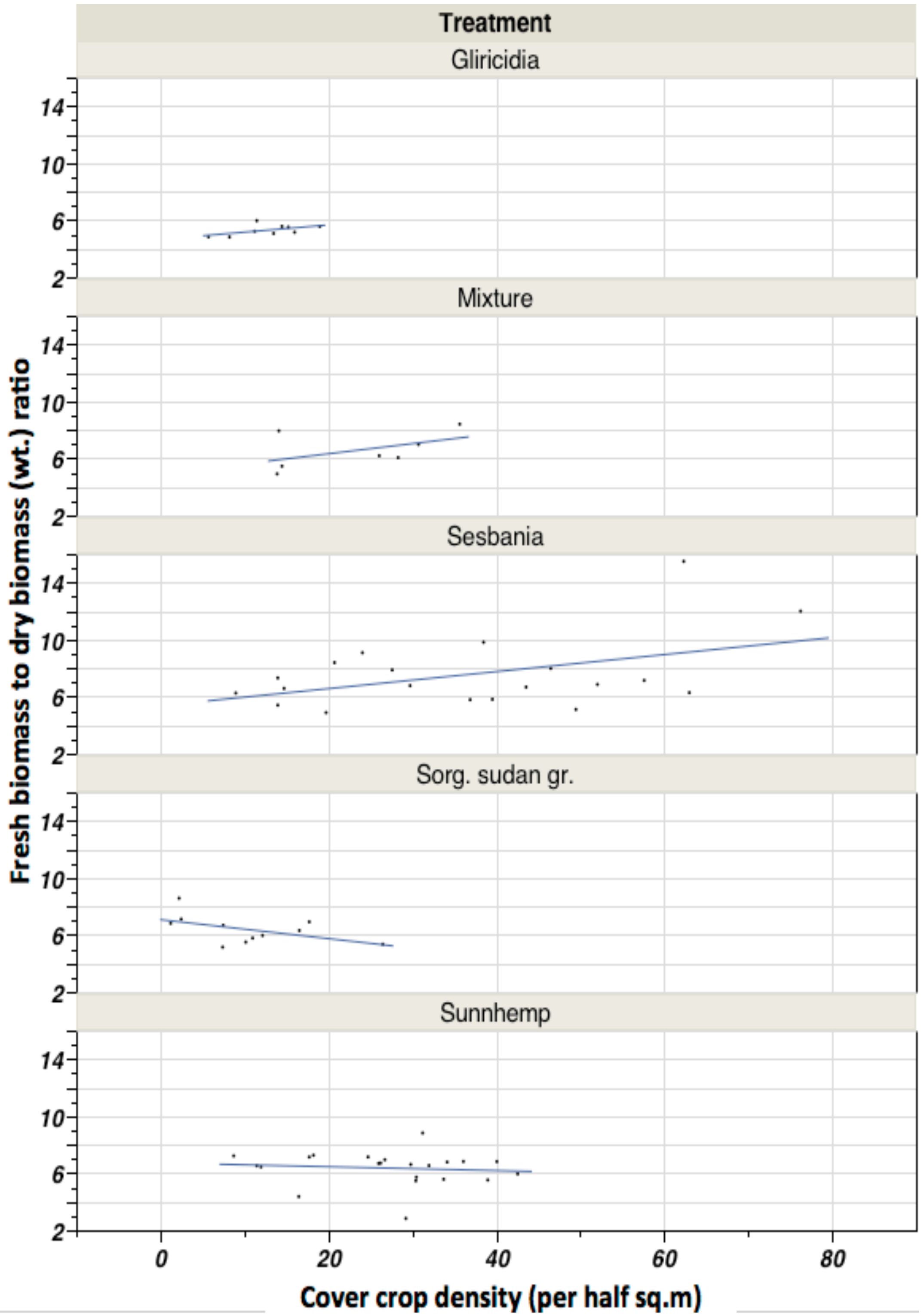


Fig. 5. Response of weed ground cover to density of the different cover crop stands. Data from all four trial sites and both years were combined.

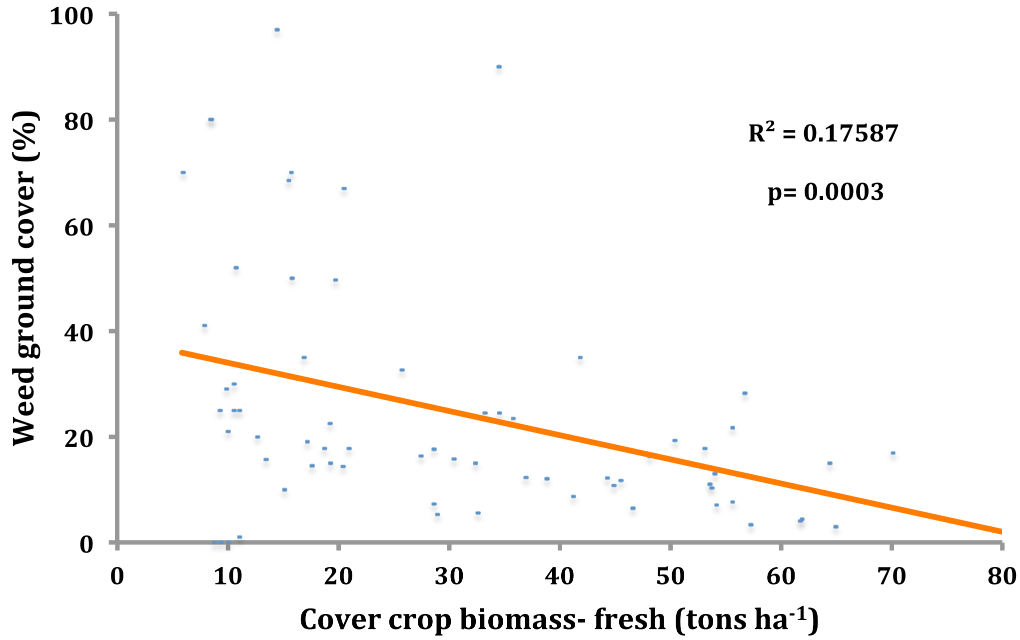


Fig. 6. Response (linear regression; α= 0.05) of weed ground cover to amount of cover crop biomass. Data from all four trial sites and both years were combined.

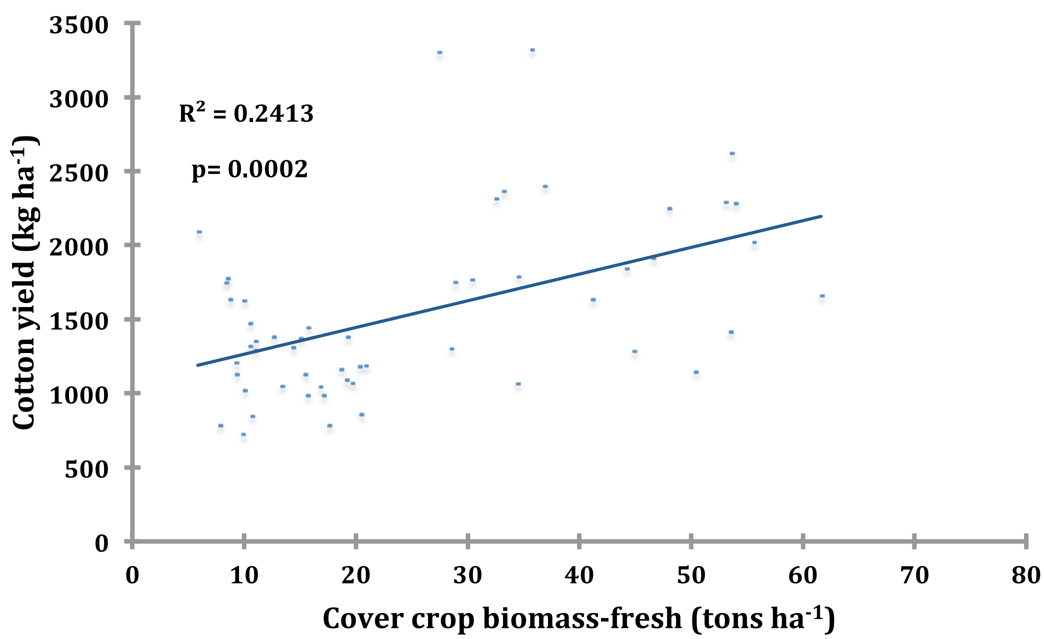


Fig. 7. Response (linear regression; α= 0.05) of cotton yield to amount of cover crop biomass produced. Data from all four trial sites and both years were combined. Site 3 has been excluded.

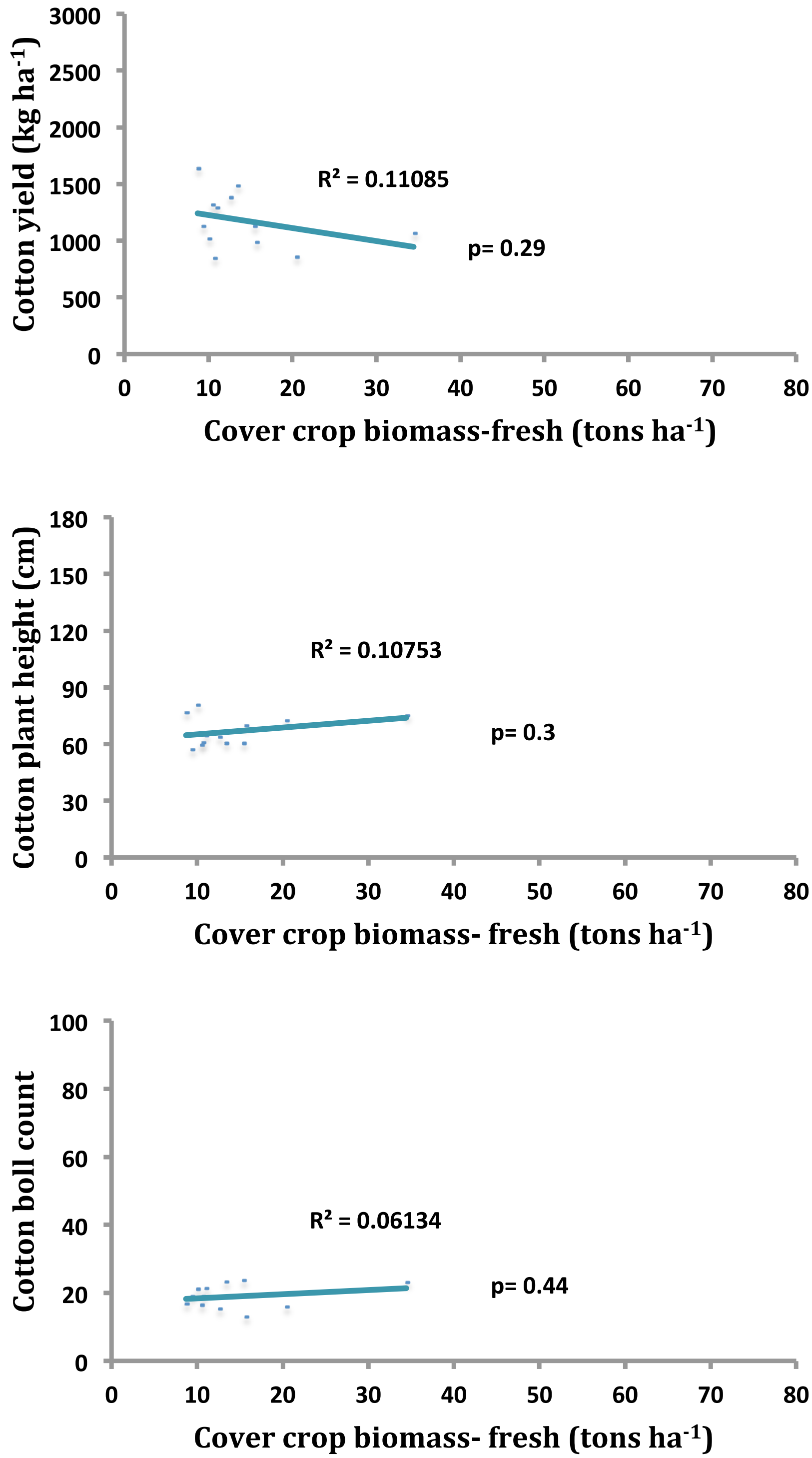


Fig. 8. Response (linear regression; α= 0.05) of cotton yield (top), cotton plant height (center) and cotton boll count (bottom) to amount of cover crop biomass produced at Site 1 during Year 1.

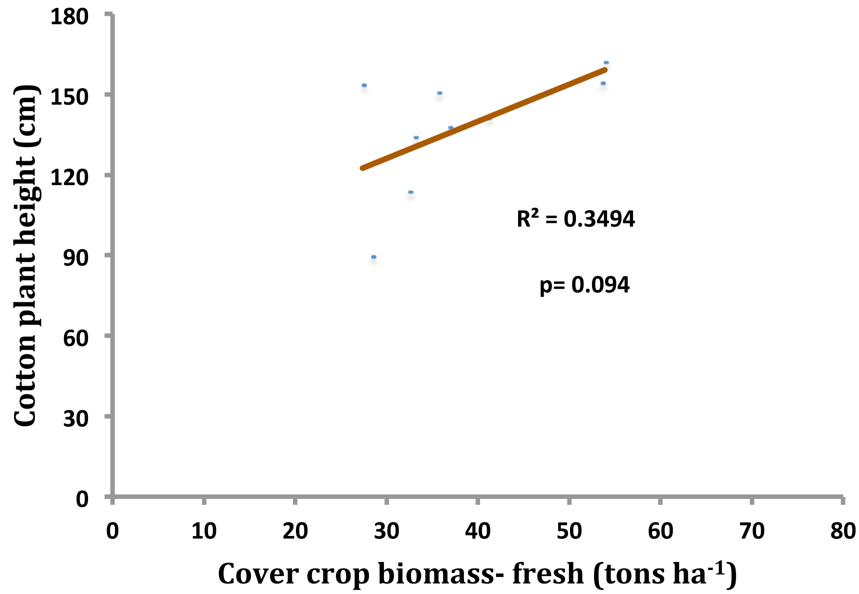


Fig. 9. Response (linear regression; α= 0.05) of cotton plant height to amount of cover crop biomass produced at Site 2 during Year 2.

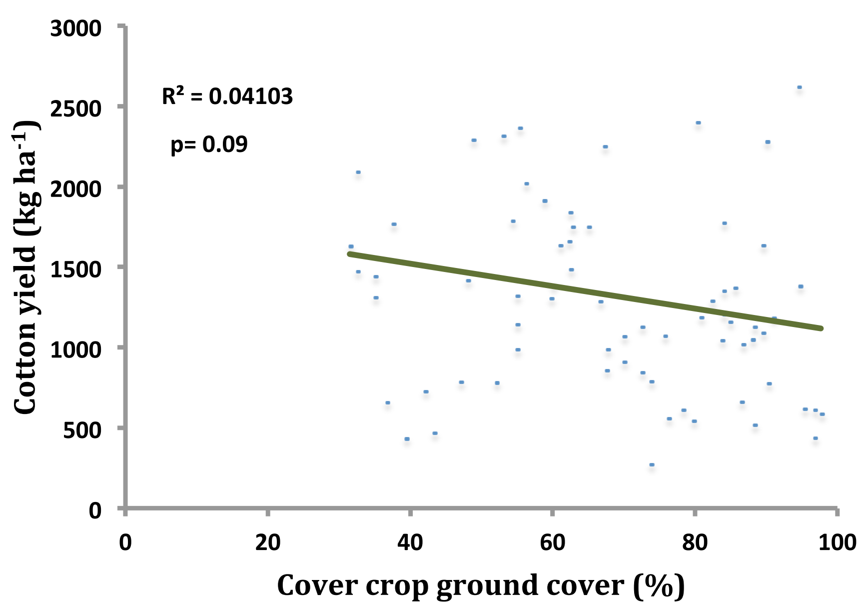
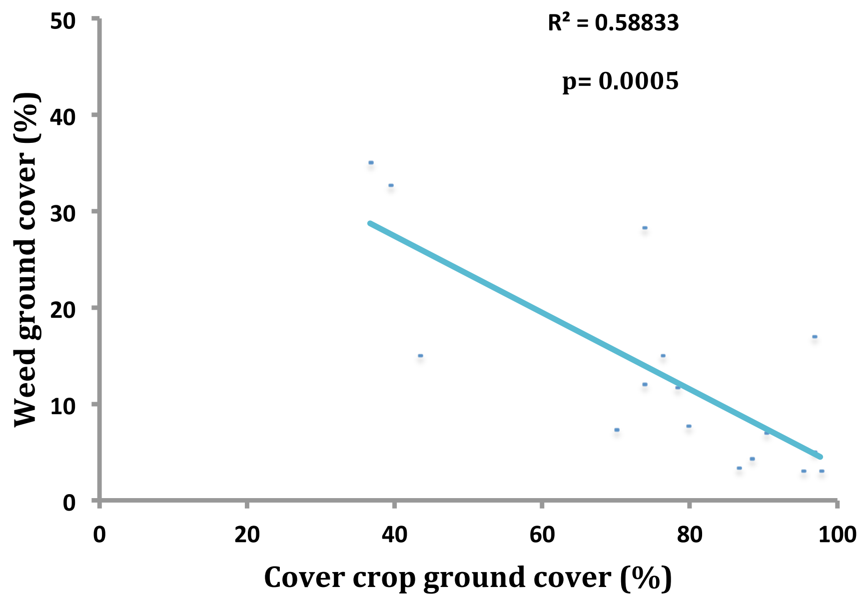


Fig. 10. Response (linear regression; α= 0.05) of cotton yield to extent of cover crop ground cover. Data from all four trial sites and both years were combined. Control plots and lablab treatment were excluded.



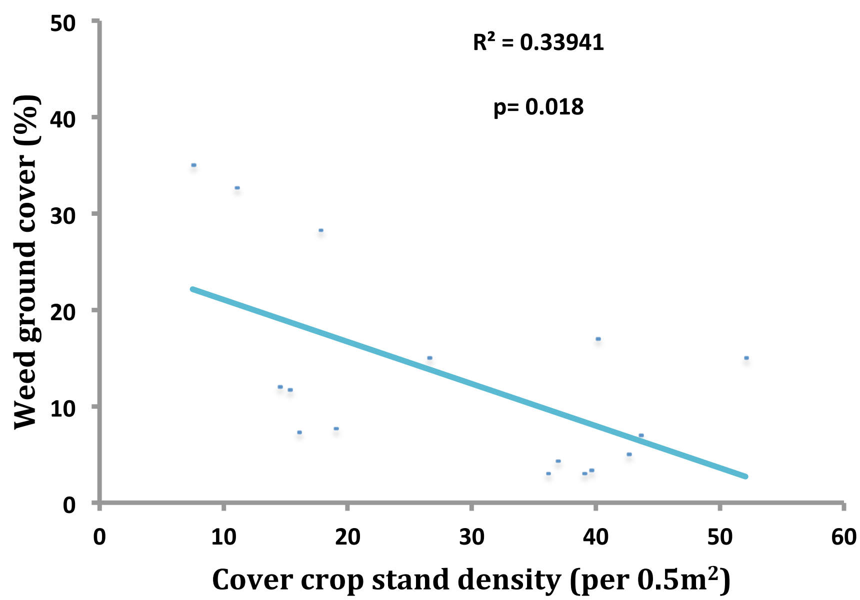


Fig. 11. Response (linear regression; α= 0.05) of the extent of weed ground cover to the extent of cover crop ground cover (top) and cover crop stand density (bottom) at Site 3. Control plots and lablab treatment were excluded.

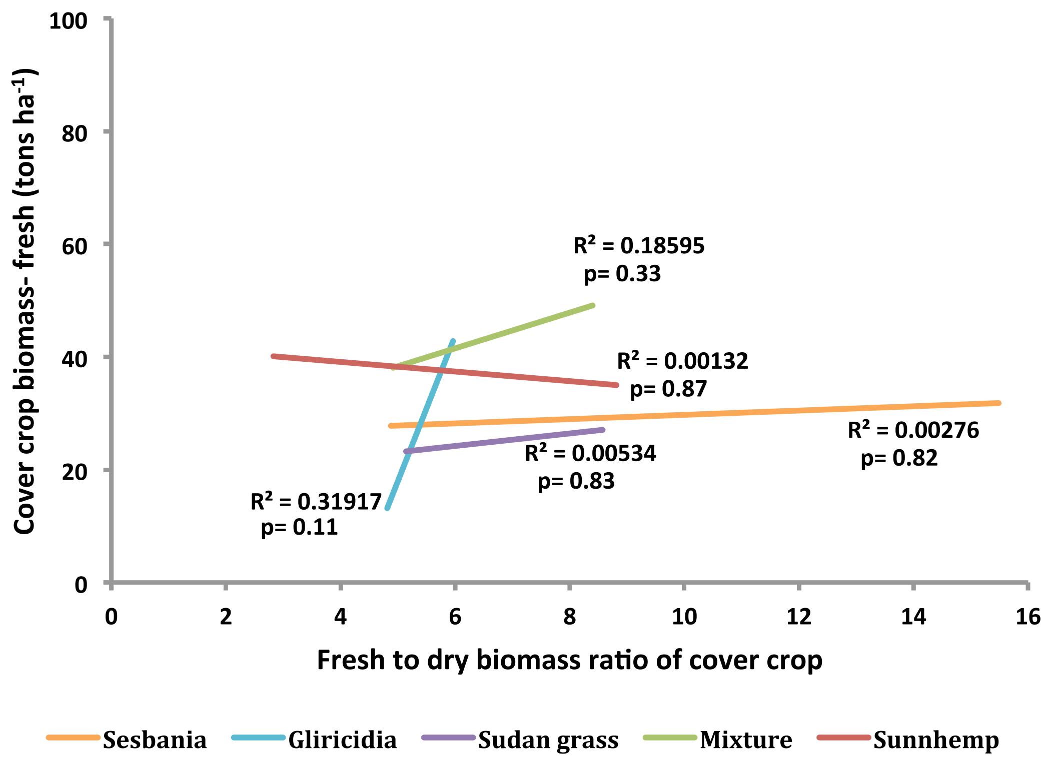


Fig. 12. Response (linear regression; α= 0.05) of amount of cover crop biomass to the ratio of fresh to dry cover crop biomass for each treatment. Data from all four trial sites and both years were combined.