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Review

Can the productivity of mango orchards be increased by using high-density plantings?

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ABSTRACT

Mango (*Mangifera indica*) trees are traditionally established at about 100–200 trees per ha and eventually grow into large specimens 10 m tall or more, making spraying and harvesting difficult. It also takes a long time to recover the initial costs of establishing and maintaining the orchard. There has been considerable interest in planting orchards up to 4000 trees per ha to take advantage of early production and to increase economic returns. However, trees planted at high density soon begin to crowd and shade each other and production falls. We reviewed the performance of high-density orchards in different growing areas, and the role of dwarfing cultivars and rootstocks, tree canopy management and the growth regulator, paclobutrazol to control tree growth. There has been no general agreement on the optimum planting density for commercial orchards which vary from 200–4000 trees per ha in different experiments. Some potential dwarfing material has been developed in India and elsewhere, but these cultivars and rootstocks have not been widely integrated into high-density orchards. Canopy management needs to take into account the effect of pruning on the regrowth of the shoots and branches, light distribution through the canopy and the loss of the leaves that support the developing crop. Pruning must also take into account the effect of vegetative growth on flower initiation. Annual light pruning usually provides better fruit production than more severe pruning conducted less regularly. There have only been a few cases where it has been demonstrated that paclobutrazol can counteract the negative effect of pruning on flowering and fruit production. There are also concerns with residues of this chemical in export markets and contamination of ground waters. The future development of high-density plantings in this crop is dependent on the use of dwarfing cultivars and/or rootstocks and better canopy management strategies. Dwarfing cultivars and rootstocks should provide small- to medium-sized trees with medium to large yields. This can readily be identified in experiments by examining the relationship between yield and tree growth. Research on canopy management should assess the impact of pruning on flowering, light distribution within the canopy and the leaf area supporting the developing crop. The productivity of mango is not likely to be increased by the use of high-density plantings without extensive efforts in plant breeding and canopy management.

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1. Introduction

Mango (*Mangifera indica*) is a member of the family Anacardiaceae from Asia and has been cultivated for at least 4000 years (Crane, 2008). It is one of the most important members of this family. It is ranked fifth in overall fruit production worldwide (Normand et al., 2015). Other popular large trees from the same family include cashew (*Anacardium occidentale*) from tropical America and pistachio (*Pistacia vera*) from Iran and Central Asia, both important nut crops. Related fruit trees include marula (*Sclerocarya birrea*) from Africa and Madagascar, and yellow mombin or tropical plum (*Spondias mombin*) from tropical and subtropical South America.

The main centre of origin for mango is within the region between north-east India and Myanmar (Crane, 2008; Bompard, 2009; Dinesh et al., 2015a; Sherman et al., 2015; Krishnapillai and Wijeratnam, 2016; Sahu et al., 2016). India is considered to be the centre of domestication of mono-embryonic cultivars, while South-east Asia including Indonesia, the Philippines, Thailand, Vietnam and Myanmar is the main centre for poly-embryonic cultivars. The poly-embryonic cultivars produce a seed with several genetically identical embryos. Cultivars from India tend to have highly coloured skin at maturity and are susceptible to anthracnose, *Colletotrichum gloeosporoides*. In contrast, cultivars from South-east Asia tend to have green to yellow skin and are less susceptible to anthracnose. Cultivars from the two main groups hybridize readily and this gives rise to a wide variation in the productivity and quality of commercial material.

Many of the cultivars grown in India are at least 400 years old (Mukherjee et al., 1968). There are more than 100 different cultivars in some parts of India, including West Bengal (Mitra et al., 2015). Productivity is strongly dependent on environmental conditions, with cultivars not always performing well when introduced to new growing areas (Costa, 2004; Le Lagadec and Köhne, 2004).

Total world mango production is more than 40 million tonnes, with only 3% of the crop traded around the globe (Evans and Mendoza, 2009; Gallo, 2015; Galán Saúco, 2015; Balyan et al., 2015; Mitra, 2016). India is the most important producing country, and accounts for nearly 40% of total world production. Other important mango growing countries include China (11%), Kenya (7%), Thailand (6%), Indonesia (6%), Pakistan (6%), Mexico (5%), Brazil (3%), and Bangladesh (2%). Although India is the main producer, it accounts for only about 16% of world mango trade. Exports are more important for Mexico, with 20% of total world trade. Other important exporting countries include Thailand (11%), Brazil (9%), Peru (9%), and Pakistan (7%). The United States and Europe are the main markets for imported mangoes. Mexico is by far the main supplier to North America, while Brazil and Peru are the main suppliers to Europe (Galán Saúco, 2000; Gallo, 2015). India exports mainly to the United Arab Emirates and other countries in the Middle East (Balyan et al., 2015).

Mango orchards are normally planted at fairly wide spacings because the trees can grow into large specimens. Non-domesticated wild seedling trees often grow up to 10 m in suitable environments (Khan et al., 2015). Traditional orchards are commonly planted out at 100–200 trees per ha. Yields per unit area are low for the first few years after planting and keep increasing until the trees start to shade each other. This period can last from ten to twenty years. There is usually a long period to recover the costs of planting and establishment under this scenario. Trees are planted on a range of different rootstocks and pruned in various ways, which affects the performance of the trees and the commercial life of the orchard. There is strong interest in the use of plantings up to 4000 trees per ha to increase the long-term productivity and economics of growing mango, with several studies in India, South Africa and elsewhere (Fivaz, 2009; Gunjate et al., 2004; Gunjate, 2009; Oosthuyse, 2009; Bally and Ibell, 2015; Kumar, 2015).

Early experiments conducted in India showed that an orchard of 'Amrapali' planted at 1600 trees per ha yielded 12, 13, 17 and 22 t per ha in the four to seven years after planting (Majumder et al., 1982; Majumder and Sharma, 1989). These yields were well above the average national yield of 9 t per ha. Yields usually start to decline after ten or twelve years in these orchards as they do in traditional plantings due to overcrowding and shading (Singh et al., 2010). The lower shoots start to die, productivity falls, and the trees become susceptible to pests and diseases. In the experiments of Majumder et al. (1982) and of Majumder and Sharma (1989), the trees were grown on unnamed seedling rootstocks. There was no indication if the trees were pruned or not. Majumder et al. (1982) noted that the trees were relatively slow growing and were about 2 m high after seven years.

Rajbhar et al. (2016) investigated the productivity of mango trees planted at high density in Uttar Pradesh. After 11 years, the yields of the plots planted at 1111 trees per ha were more than ten times the yields of plots planted at 100 trees per ha (59 t per ha versus 5.9 t per ha). The trees growing in the close plantings were beginning to grow into each other (canopy diameter of about 3 m) and needed to be pruned after harvest. Many of the orchards in India are grown on relatively poor soils and are dependent on rainfall, and pest control is highly variable. These factors contribute to low productivity in many growing areas.

Intensive orchard management systems based on high-density plantings have been implemented to various degrees in apple, pear, cherry and stonefruit for more than 50 years (Tustin, 2014). In these crops, the success of the new orchards has been based on the availability of suitable dwarfing rootstocks and productive scions. The architecture of the trees is carefully manipulated to improve the capture and distribution of sunlight throughout the canopy. Research conducted in apples where the technology is well developed has demonstrated that there is a strong relationship between productivity and light interception across different cultivars and growing environments (Wünsche and Lakso, 2000; Palmer et al., 2002). In some areas with low radiation levels, yields often increase with increasing light interception, although in areas with high radiation levels, the leaves and the fruit can be damaged by excessive light and high temperatures in summer (Corelli-Grappadelli and Lakso, 2007). In a study in pear in the United States, a high-density planting came into production sooner, showing a profit after six years compared with nine years for the traditional planting (Elkins et al., 2008). The costs of establishing the orchards were recovered after ten years in the high-density planting compared with twenty-one years for the traditional planting.

A review of productivity in olives indicated that the main factors influencing the success of high-density orchards included the vigour and productivity of the scion, the availability of at least semi-dwarfing rootstocks, soil type, growing conditions and economics (Trentacoste et al., 2015a,c). Low to medium vigour cultivars responded better to pruning in high-density groves than medium to high vigour cultivars (Trentacoste et al., 2015b; Vivaldi et al., 2015). Higher yields were obtained from low to medium vigour cultivars after topping, hedging and thinning. Higher yields in close plantings are associated with greater light interception due to the greater density of plants and greater absorption of light per unit of leaf area (Morales et al., 2016).

We report on the factors influencing the productivity of high-density plantings of mango trees growing in different environments. Strategies used to control the growth of the trees are explored. These include pruning systems, growth regulators such as paclobutrazol, dwarfing rootstocks and dwarfing scions. Possible management systems for future orchards are discussed. This review follows a previous analysis of high-density plantings in avocado (Menzel and Le Lagadec, 2014). Where available, the data presented in the tables have been accompanied by the results of statistical tests of the original authors. This was not generally possible with the data presented in the figures, with no statistical tests applied by the original authors, or the data were meaned over different years or different cultivars.

2. Productivity of commercial orchards

Productivity in mango varies dramatically across different growing areas, and across different orchards within a particular growing area. Sukonthasing et al. (1991) suggested that mean yields in South-east Asia are quite low at about 5 t per ha. A yield of 10 t per ha is considered good for high quality tropical cultivars and 10–30 t per ha is considered good for subtropical cultivars. Average yields for productive orchards in some growing environments are about 22–25 t per ha (Crane, 2008). A good yield for a well-managed orchard in Thailand is about 25 t per ha (de Bie, 2004). Average yields are about 16 t per ha in Brazil about double of that recorded in India (Carr, 2014; Shenoy and Rajagopalan, 2016). In a survey of orchards in Maharashtra, the average productivity of orchards across all ages up to orchards more than 50-years-old ranged from 3 to 5 t per ha (Talathi et al., 2015). Yields have been relatively stable in India recently, with total production increasing mainly because of increasing plantings (Balyan et al., 2015). A high proportion of the orchards in South-east Asia are very old and relatively unproductive. Yields often increase up to about year ten and then decrease (Rajput et al., 1999).

Mango trees are often irregular in their cropping habit, with no clear pattern across different years. Plantings can also suffer from alternate or biennial bearing, where a tree or an orchard produces a large crop in an on-year followed by a small crop in the following off-year (Souza et al., 2004). There can be periods of irregular bearing and periods of alternate bearing in the same orchard (Fitchett et al., 2016). In Thailand, yields of 'Chok Anan' varied considerable between years (Spreer et al., 2009). Between 38 and 75% of the trees in a single orchard bore alternately, with heavy crops in one year followed by poor flowering and fruit set the following year. Souza et al. (2004) studied the pattern of fruiting in 19 cultivars over 18 years in Brazil. Alternate bearing occurred in some cultivars and worsened as the trees aged. Other cultivars displayed a pattern of alternate bearing for a few years of production and were classified as having a low alternate bearing behaviour. Other cultivars showed an erratic behaviour with no clear pattern of alternate bearing, and certainly no regular bearing. For example, 'Alphonso' yielded 20 t per ha for four cycles and then had progressively lower yields for the next three cycles.

The analysis of alternate bearing can be complicated because poor weather can reduce cropping in an on-year. Singh et al. (2014a) studied the performance of 100 'Langra' trees over five years in Lucknow in India. Their analysis took into account the effect of individual seasons and individual trees on yield and showed that the orchard had a distinct pattern of alternate bearing. Average yields in the orchard over the period ranged from 26 to 107 kg per tree. Research in Réunion Island demonstrated that alternate bearing varied widely across four different cultivars (Dambreville et al., 2014). Flowering and fruit set were regular across three growth cycles in 'Irwin' and 'Kensington Pride'. In contrast, there were alternating patterns of vegetative and reproductive growth in 'Cogshall' and 'José'.

3. Photosynthesis and light interception

Productivity in trees is dependent on the capture of light by the canopy and the translocation of photosynthates to the developing crop. There is usually a strong relationship between fruit size and the number of leaves supporting an individual fruit (Urban and Léchaudel, 2005). The amount of photosynthates produced by a tree depends on environmental conditions and the physiology of the leaves. The two main factors affecting potential photosynthesis is the distribution of light and nitrogen within the canopy (Menzel and Le Lagadec, 2014). Plants usually allocate nitrogen resources within the canopy to enhance photosynthesis in locations that are exposed to good illumination. Leaves developing in different parts of the canopy can also adapt to the local light environment.

Urban et al. (2003) measured the photosynthetic capacity, carbohydrate concentrations and nitrogen concentrations of leaves in the different parts of mango trees growing in Réunion Island. The incidence of diffuse radiation in different positions in the canopy was estimated as a fraction of total incident radiation under overcast conditions. These workers found that the concentration of nitrogen (N_a) and the concentration of total non-structural carbohydrates (T_a) on a leaf-area-basis increased linearly with incident light levels. Similar relationships were found for all leaves irrespective of their age. Photosynthetic capacity, as measured by the maximum rate of carboxylation (V_{cmax}) or the light-saturated rate of electron transport (J_{max}), was correlated with N_a. Photosynthetic acclimation to light was also driven by changes in leaf mass-to-area ratio (M_a). The results of these studies demonstrate the strong relationship between photosynthesis, leaf nitrogen, leaf anatomy and light in mango trees.

Mango trees require a relatively high level of irradiance to saturate photosynthesis and this high value suggests that the trees are adapted to growing in full sun conditions. Whiley et al. (1999) found that net CO_2 assimilation (A) in leaves of 'Kensington Pride' in southern Queensland was saturated (Q value) at a photosynthetic photon flux (PPF), also referred as photosynthetic active radiation (PAR) of 1270 μmol per m^2 per s in field-grown trees and at 563 μmol per m^2 per s in container-grown trees (early autumn). When the trees in the field were sampled in winter when minimum daily temperatures were below 10 °C, A was saturated at a slightly lower PFF of 1180 μmol per m^2 per s. Maximum values of A were highest in the leaves sampled in autumn from field-grown trees. Schaffer and Gaye (1989a) grew trees in containers in Florida and found that Q was similar for leaves grown at 25, 50, 75 or 100% full sun for four weeks at about 350 μmol per m^2 per s. Leaves that developed in the full sun had higher values of A than leaves that developed in the shade.

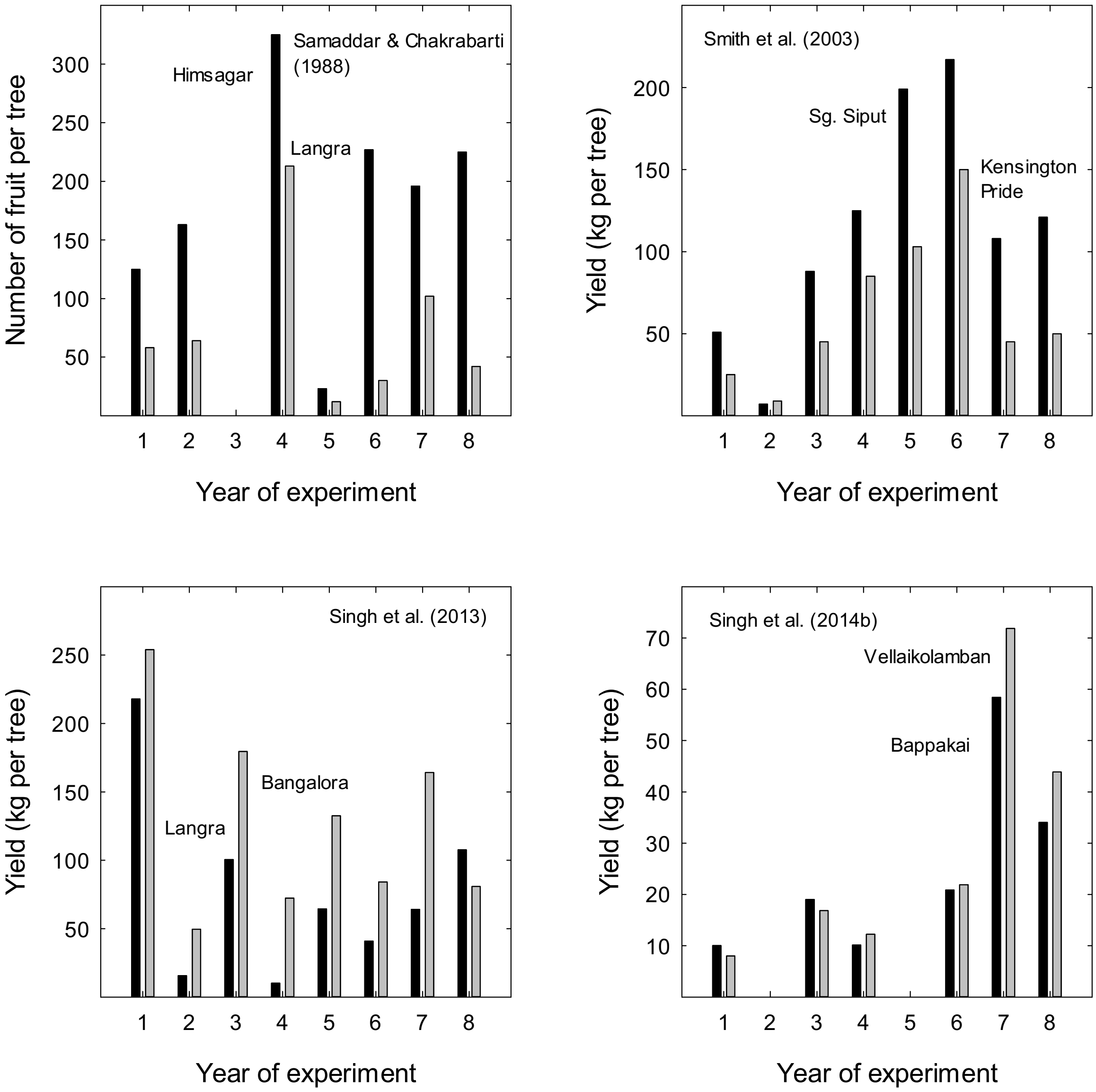

Fig. 1. Changes in fruit production over time in various mango orchards in India and Australia. Maximum production occurred in year four (Samaddar and Chakrabarti, 1988 with two cultivars), or in years five and six (Smith et al., 2003 with 'Kensington Pride' on two rootstocks) or in year seven (Singh et al., 2014b with two cultivars), or decreased over time (Singh et al., 2013 with two cultivars). The trees were 15-, 2-, 28- and 25-years-old at the start of these experiments, respectively. Data are adapted from the various sources.

Durand (1997) examined the relationship between light interception and tree architecture in Venezuela. The amount of light penetrating the canopy decreased inside the canopy of the trees in proportion to the leaf area index (LAI). The results of experiments conducted in India and Florida showed that pruning increased the penetration of light through the canopy and increased the rate of photosynthesis (Schaffer and Gaye, 1989b; Pratap et al., 2003; Sharma et al., 2006). None of these studies defined a minimum light level required for successful fruiting in the crop.

Temperature is a major environmental factor influencing photosynthesis in mango. Pongsomboom et al. (1992) found that net CO_2 assimilation (A) in 'Nam Dok Mai' growing in a glasshouse was higher at day/night temperatures of 30°/20 °C than at day/night temperatures of 15°/10 °C. Weng et al. (2013) showed that saturated values of A were 5.7, 7.2, 9.6, and 11.8 μmol CO_2 per m^2 per s at 13°, 18°, 24° and 30 °C, respectively. Researchers in Japan showed that at a vapour pressure deficit (VPD) of 1.5 kPa, A was higher in 'Irwin' trees growing at 40°/25 °C than at 30°/25 °C (Talwar et al., 2001). Schaffer et al. (2009) indicated that photosynthesis increases with temperature up to about 45 °C. This is consistent with published data for a range of temperate and tropical species (Medlyn et al., 2002). Tree species from warm climates had higher temperature optima than species from cool climates for both V_{cmax} and J_{max}.

Low temperatures are possibly more important in controlling photosynthesis in mango than high temperatures. Allen et al. (2000) indicated that chilling temperatures of 5° or 7 °C overnight reduced midday values of A in 'Tommy Atkins' trees growing in a glasshouse in Florida. There was a 50% decline in gas exchange at midday compared with the control trees growing at 30 °C. Net CO_2 assimilation recovered to control values by the end of the day.

Several researchers have shown that there are strong seasonal changes in photosynthesis in mango. González and Blaikie (2003) showed that A_{max} varied over the year in 'Kensington Pride' trees growing in the Northern Territory in Australia, and ranged from 9.1 μmol CO_2 per m^2 per s during the wet season to 4.2 μmol CO_2 per m^2 per s during the dry season. More than 70% of the variation in A_{max} could be explained by changes in vapour pressure deficit

(VPD). Similar data were obtained in a later study conducted by Lu et al. (2012) with five cultivars in the same area, with a strong negative relationship between A and VPD over the growing season. Elsheery et al. (2007) found that average values of A_{max} in five cultivars in Yunnan in China were lower in the cold, dry season ($9.5 \pm 0.6\,\mu$mol CO_2 per m^2 per s) (mean ± standard error or SE) and higher in the hot, dry season ($15.9 \pm 0.2\,\mu$mol CO_2 per m^2 per s) and hot, wet season ($17.7 \pm 0.2\,\mu$mol CO_2 per m^2 per s). In this study, the five cultivars had similar average values of A_{max}. A similar response was recorded for eight cultivars from four different growing areas in India (Rymbai et al., 2014). Data collected over a single morning showed that A ranged from 6.9 to 11.0 μmol CO_2 per m^2 per s.

Lu et al. (2012) calculated the total yearly values of CO_2 assimilation across the five cultivars and found that it ranged from 198 to 351 μmol CO_2 per m^2 per s. There was no clear relationship between yield per unit of canopy surface area and total dry season or yearly A. This was because poor flowering in some cultivars reduced potential yield. In a study conducted in India with nucellar seedlings of 16 poly-embryonic cultivars, there was a strong correlation ($r = 0.85$) between plant dry weight and mean values of A (Srivastav et al., 2009). It was not determined whether the higher growth rate in some cultivars was related to higher productivity.

The leaves of mango trees can change colour as they develop from red or chocolate brown to light green and finally to dark green. The pattern of colour development typically varies with the cultivar. The immature leaves are initially net importers of carbon and only begin to contribute to the carbon economy of the shoot as they expand. Typically, net CO_2 assimilation increases as the leaves expand and accumulate chlorophyll. Work in Japan using seedlings and young trees growing in containers showed that the full leaf expansion occurred about 10–12 days after the buds emerged, whereas the concentration of chlorophyll per unit of leaf area increased up to day 30 or 60 (Nii et al., 1995; Ali et al., 1999). In both these studies, there was a strong relationship between photosynthesis and the concentration of chlorophyll in the leaves.

In India, small differences in CO_2 assimilation (A) across different cultivars were related to differences in the thickness of the leaves and the concentration of chlorophyll per unit of leaf area (Tyagi and Devi, 1988; Pandey and Tyagi, 1999). High rates of carbon assimilation occurred in thin leaves with high concentrations of chlorophyll. Yadava and Singh (1995) indicated that photosynthesis varied with the age and position of the leaves on the branches. Mature leaves had higher values of A than young or old leaves. Leaves in the middle and upper positions of the shoot had higher values of A than leaves in the lower positions of the shoots. Differences in A in the leaves were related to differences in light exposure and temperatures, and the thickness of the mesophyll. In other studies in Brazil, leaves in the centre of the tree generally had lower rates of photosynthesis than leaves in the outer canopy (Almeida et al., 2015).

Reproductive development can also alter the rate of photosynthesis in the leaves of mango trees. Urban et al. (2008) found that leaves closer to inflorescences had lower A and lower J_{max} compared with leaves further away from inflorescences. They concluded that the response was due to decrease in leaf nitrogen (N_a), and that the effect was reversible. Photosynthetic parameters measured on leaves close to inflorescences with fruit were generally intermediate to those measured on leafy shoots and on leaves close to inflorescences without fruit. Earlier work demonstrated that photosynthetic capacity (V_{cmax} and J_{max}) increased with crop load in girdled branches (Urban et al., 2004). The results of these various studies indicate that photosynthetic capacity in the developing leaves is reflected by changes in the light environment and leaf chlorophyll. It is also apparent that fruiting generally increases photosynthetic capacity with a temporary decrease during flowering.

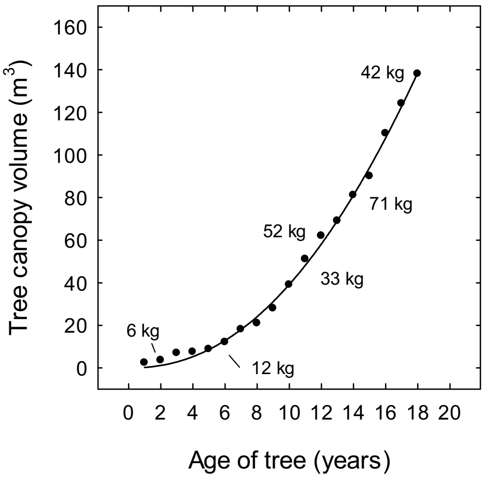

Fig. 2. Changes in tree canopy volume in 'Alphonso' mango grown in India over 18 years. Yields (kg per tree) for selected years shown. There were eleven years with little or no yields, one year with medium yields, and five years with high yields in seventeen years of cropping. Data are adapted from Reddy et al. (2003).

4. Relationship between productivity, tree growth and light interception

There are few studies that have examined the relationship between tree growth, productivity and light in mango. One of the problems in analysing the productivity of mango orchards over time is the tendency for some cultivars to be biennial or irregular in their flowering and fruiting behaviour. Only a few of the reports on productivity provide information on the yields for more than five years. This makes it difficult to determine how quickly production declines in old trees as they begin to shade each other. Bally et al. (2002) noted that there was an almost linear increase in the yields of 'Kensington Pride' selections over ten years in northern Australia ($P = 0.002$). The modelled yield after ten years was about 150 kg per tree. These results suggest that the trees were growing slowly and not shading each other in this dry environment.

Examples of productivity in mango orchards over time are shown in Fig. 1. These data present yields over eight years in experiments conducted in India and Australia. This analysis shows that yields fluctuated over the period, reflecting biennial or irregular bearing in the orchards. In the studies by Samaddar and Chakrabarti (1988) and Smith et al. (2003), the highest average yields tended to occur in year four or years five and six, with lower yields thereafter. In the study by Singh et al. (2013), average yields tended to decrease over time. In these examples, there is some evidence that the older trees began to shade each other and that this affected fruit production. In the two studies conducted in India, the authors did not mention whether the trees were pruned during the experiment. In the study conducted in Australia, Smith et al. (2003) indicated that the trees were lightly pruned to remove some internal branches to improve the penetration of chemical sprays. In the final study conducted by Singh et al. (2014a), average yields tended to increase up to year seven and then decreased. The authors indicated that the trees were maintained under uniform cultural conditions, but did not mention any canopy management practices. Once again, the older trees appear to have started shading each other, and productivity declined.

Reddy et al. (2003) reported on the growth and yield of 'Alphonso' trees growing in Bangalore over 18 years. Out of seventeen cropping seasons, there were eleven years with little to no yields, one year with medium yields, and five years with high yields. There was no apparent pattern of alternate production. In this experiment, tree canopy volume increased over time in an

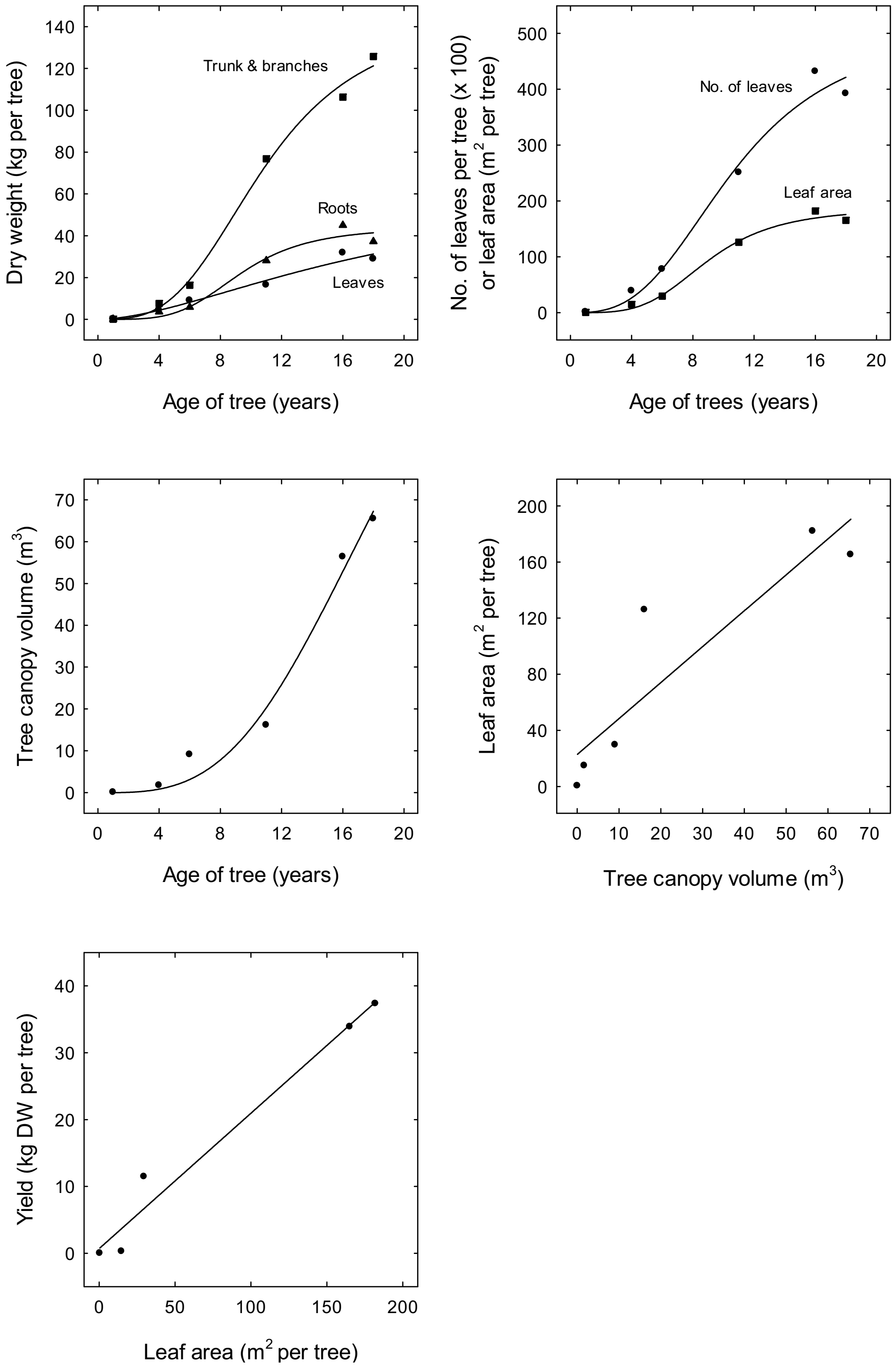

Fig. 3. Changes in vegetative growth, leaf area, canopy volume and yield in 'Sensation' mango trees grown in South Africa. The yields of the 11-year-old trees were very low (mean and standard deviation, 1.5 ± 0.4 kg per tree) and were excluded from the analysis. Data are adapted from Davie and Stassen (1997).

exponential pattern at least up to 19 or 20 years (Fig. 2). Yields in the better years tended to increase as the trees grew, with a decrease in the last year. It was difficult to determine the exact relationship between yield and tree canopy volume because of the irregularity of cropping. Potential yield seemed to increase until the second last year of the experiment.

Davie and Stassen (1997) collected data on leaf development, dry matter production and yield of 'Sensation' trees growing in South Africa. The trees ranged in age from one- to eighteen-years old. The trees were felled and separated into the leaves, trunk, branches, roots, and fruit, while information was also kept on the number of leaves on each tree and total leaf area. All the trees were felled at the same time and none of the trees were pruned during the study. The authors did not indicate the number of trees in each age category. Increases in tree growth over time followed sigmoid patterns (Fig. 3) (except for leaf dry weight over time which was linear). The trunk and the branches accounted for 56% of dry matter production in the old trees, whereas the leaves (13%), roots

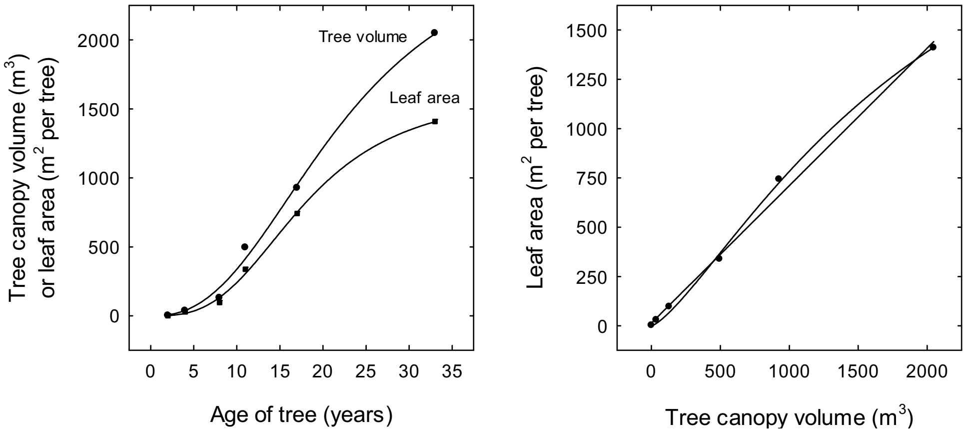

Fig. 4. Changes in leaf area and tree canopy volume in 'Palmer' mango trees grown in Nigeria. The two possible relationships (linear and logistic) between leaf area and tree canopy volume also shown in the second figure. No data were provided on fruit production. Data are adapted from Oguntunde et al. (2011).

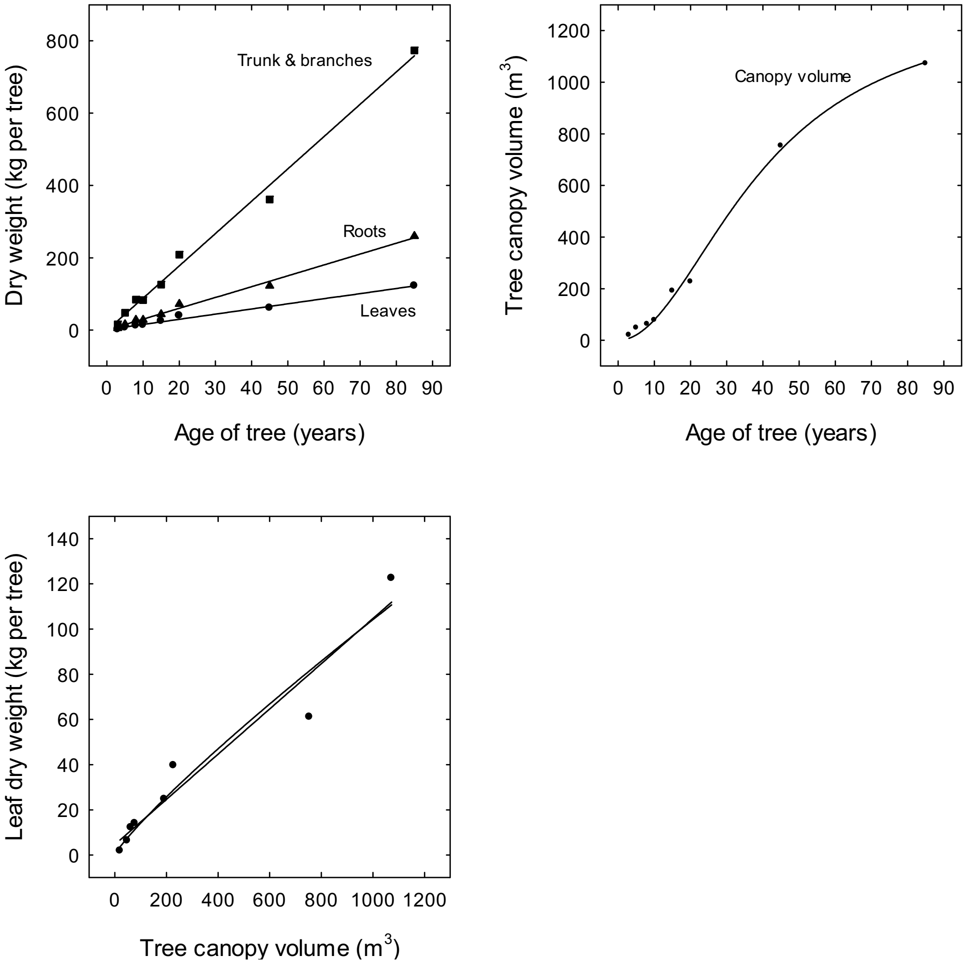

Fig. 5. Changes in vegetative growth and tree canopy volume in mango trees grown in India. The two possible relationships (linear and logistic) between leaf dry weight and tree canopy volume also shown in the third figure. No data were provided on fruit production. The cultivar was not specified. Data are adapted from Ganeshamurthy et al. (2016).

(16%) and the fruit (15%) were minor components of dry matter. Changes in leaf production and leaf area over time also followed sigmoid patterns, with similar leaf areas in the 16- and 18-year-old trees. Tree canopy volume calculated from measurements of tree height and canopy spread also increased over time in a sigmoid pattern. There were strong relationships between leaf area per tree and tree canopy volume ($R^2 = 0.79$; Fig. 3), and between yield and leaf area per tree ($R^2 = 0.96$; Fig. 3). The results of this experiment show that fruit production was strongly related to leaf area, at least for trees up to 18 years after planting in this environment. The fruit accounted for less than 20% of the tree's dry matter at this time, with an increasing investment in the trunk and branches.

Oguntunde et al. (2011) and Ganeshamurthy et al. (2016) explored the changes in tree growth over time for orchards in

Nigeria and India and found similar relationships as the ones documented by Davie and Stassen (1997) in South Africa. In Nigeria, the changes in tree canopy volume and leaf area per tree followed sigmoid patterns in trees from two- to thirty-three years of age (Fig. 4). In India, the changes in tree dry weight and tree canopy volume followed linear or sigmoid patterns in trees from three- to eighty-five years of age (Fig. 5). The studies of Oguntunde et al. (2011) and Ganeshamurthy et al. (2016) also demonstrated the strong relationship between leaf area or leaf dry weight per tree and tree canopy volume. Unfortunately, no data on fruit production were mentioned in these investigations. Other investigators have examined the development of the tree at the branch level. Research conducted in Réunion showed that seasonal leaf area production was related to the cross-sectional area of the new branches (Normand and Lauri, 2012). This relationship could be used to model leaf area production in different sections of the canopy by measuring the cross-sectional area of sampled branches.

There has been little research on the relationship between productivity and light interception in mango. For some crops, maximum productivity is associated with an interception of about 60–70% of sunlight (Castillo-Ruiz et al., 2016). Because of its role in photosynthesis and plant development, the interception, transmittance of solar radiation between 400 and 700 nm (photosynthetically active radiation or PAR) is often used to characterize potential productivity in different sections of the canopy (Gendron et al., 1998). Scientists from France and Thailand studied the interception of light in a single young mango tree that had produced six flushes and 168 leaves (Sinoquet et al., 1998). These workers found that light interception was higher in the younger flushes than in the older flushes, with the younger flushes at the top of the tree shading the older flushes. The young flushes had the greatest proportion of their leaves under sunlit conditions.

In later work by the same group, light interception was calculated in different tree species, including mango using the term silhouette to total area ratio or STAR (Sinoquet et al., 2005). This index expressed light interception in terms of the ratio between the leaf area which actually intercepts light and total leaf area on a specific day and at a given time of day. Usually STAR is averaged over a season or year. In this analysis, two mango trees had STAR values of 0.32 or 0.36 compared with 0.44 for a walnut tree. The lower average light levels for mango was partly related to higher leaf area densities (1.30 or 1.32 m^2 per m^3) than that recorded for walnut (0.66 m^2 per m^3).

Research in Australia showed that blush development of the skin was related to light levels in different parts of a tree (Yu et al., 2016). There were 4875 leaves and 59 fruit on the seven-year-old 'Honey Gold' tree. Most of the fruit were growing on the outer canopy of the tree, and the tree had an open canopy, suggesting the further pruning to improve light interception by the lower canopy was not likely to improve fruit quality.

Overall, information on the relationship between yield and leaf area index (LAI) in mango is sparse. Leaf area index is the total one-sided area of leaf tissue per unit of ground surface area and reflects potential photosynthesis by the canopy and potential yield (Bréda, 2003). Rajan et al. (2001) investigated light interception in 26 cultivars from different mango-growing areas in India. Leaf area index ranged from 1.2 to 4.5, while the fraction of diffuse radiation below the canopy ranged from 0.02 to 0.36. Cultivars from south and west India tended to have more open canopies and better light penetration than cultivars from north and east India. Overall, there was a strong negative relationship between radiation levels below the canopy and LAI (Fig. 6). These results highlight the strong effect of tree architecture on light interception in mango canopies. Rajan et al. (2001) did not determined whether high light levels in the lower canopy of some of the cultivars were associated with high productivity. Manipulation of tree architecture has been shown to effect light interception, growth and productivity in other crops such as apple (Willaume et al., 2004; Stephan et al., 2008).

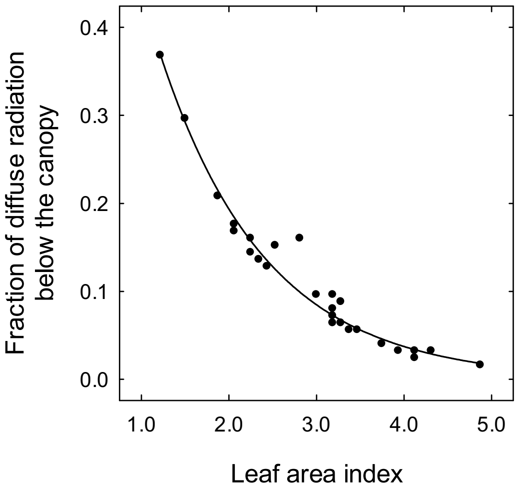

Fig. 6. Relationship between light interception and leaf area index (LAI) in 26 mango cultivars grown in India. Light interception was expressed as a fraction of diffuse radiation recorded above the canopy. Data are adapted from Rajan et al. (2001).

A few authors have studied the relationship between photosynthesis and the changes in light levels after pruning. Pruning usually increases the penetration of sunlight to the lower levels of the canopy. The rate of photosynthesis can be used as a potential index of productivity in the trees, although sometimes excessive pruning can reduce the leaf area supporting the developing crop. There were mixed relationships between net CO_2 assimilation (A) and light in the different experiments, all conducted in India (Fig. 7). In the first study, maximum rates of A occurred at intermediate light levels associated with light or moderate pruning (Pratap et al., 2003). In the second study, A increased with increasing light levels up to moderate pruning (Sharma et al., 2006). There was a separate response for the trees pruned severely, with higher light levels but lower A. In the final study, A increased with increasing light in response to more severe pruning (Singh et al., 2009). This response could have been due to the leaves on the pruned trees being younger than those on the control trees. The results of these experiments show that photosynthesis increases with moderate pruning. It is possible that severe pruning in some experiments affected the physiology of the leaves.

The relationship between productivity and ambient light levels has been well studied in some orchard and plantation crops, but not very well in mango. Trentacoste et al. (2015b) studied the productivity of olive hedgerows in Spain. They found that maximum fruit density and oil production occurred from 1.0 to 2.0 m height, with lower productivity at lower and higher positions. The poor productivity at the bottom of the canopy was associated with lower illumination than that recorded in the middle canopy. The poor productivity at the top of the canopy was associated with greater illumination but lower shoot density. In other work in olive, there were strong correlations between fruit number, fruit density, fruit fresh weight and oil concentration, and total incident radiation in different parts of the canopy (Connor et al., 2016; Trentacoste et al., 2016). Similar studies need to be conducted in mango to manipulate light levels and shoot density for maximum yield. The work in apple (Willaume et al., 2004; Stephan et al., 2008) also provides information on possible approaches to be used in studies in mango. These researchers examined the relationship between productivity and light levels in different sections of the apple canopy. Training the trees to certain shapes and removing some of the branches increased yield compared with control trees.

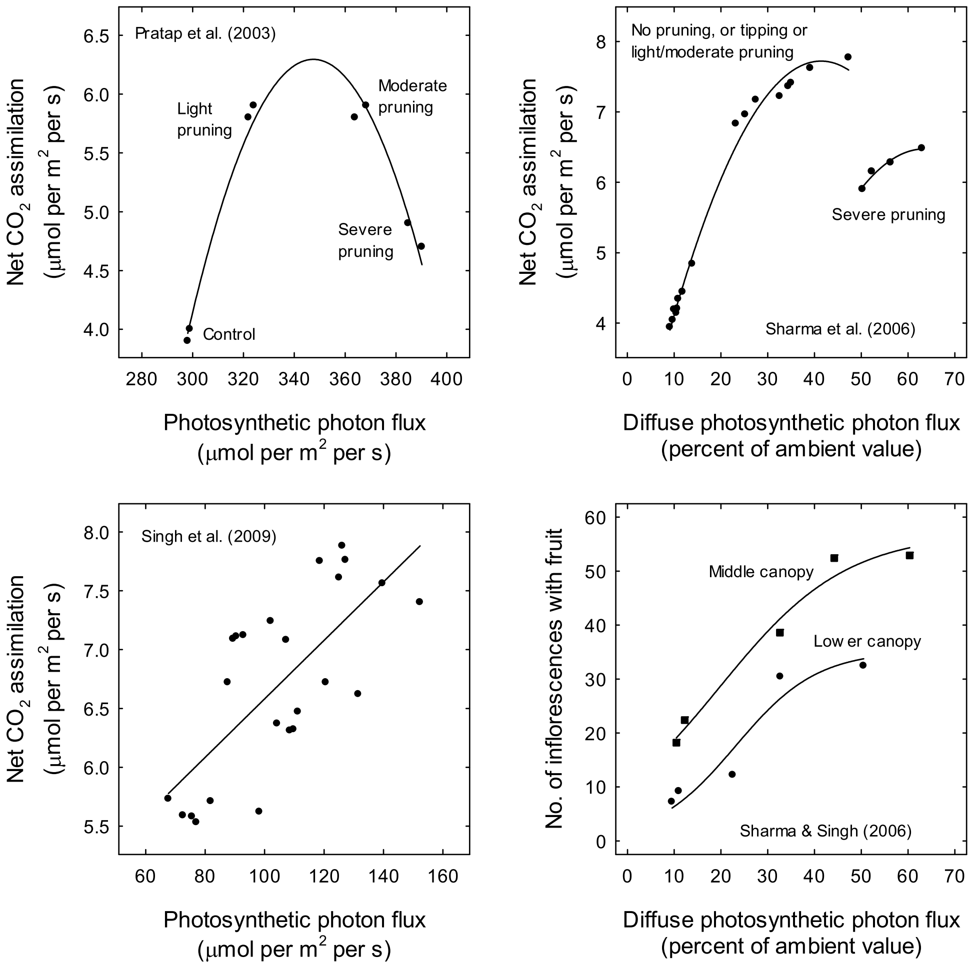

Fig. 7. Relationships between net CO_2 assimilation and light levels in mango trees pruned to different levels in India (Pratap et al., 2003; Sharma et al., 2006; Singh et al., 2009). The different light levels were associated with control trees, and various pruning treatments. The lower right hand graph shows the relationship between the number of inflorescences with fruit and light levels in two parts of the canopy after various levels of pruning (Sharma and Singh, 2006). Pruning (four higher values on each regression) increased light levels compared with control trees (lowest values on each regression). Data are adapted from the various sources.

Sharma and Singh (2006) studied the effect of pruning on productivity of different section of the canopy of 16-year-old 'Amrapali' trees growing in New Delhi. The branches were tipped to remove newly emerging shoots, or the branches pruned to remove 10, 20 or 30 cm of new growth. Control trees were left unpruned. The top section of the canopy was more productive than the lower or middle sections of the canopy. There were 48 inflorescences with fruit in the top of the canopy (3.6 m), 18 inflorescences with fruit in the middle canopy (1 m above the crotch), and 7 inflorescences with fruit in the lower canopy (0.5 m above the crotch) (LSD, $P < 0.05$, 10). Tipping and pruning increased the number of inflorescences with fruit in all sections of the tree and increased the number of inflorescences with fruit for the whole tree compared with the control (Fig. 7). The best response was obtained with moderate pruning, with severe pruning resulting in fewer inflorescences with fruit than moderate pruning in the upper canopy and for the whole tree. Pruning did not increase the relative distribution of inflorescences with fruit in the different parts of the canopy. It is possible that the severe pruning increased light levels but this was at the expense of the leaf area supporting the developing crop.

5. Productivity of high-density orchards

The recommended planting density for mango varies with the cultivar and growing environment and usually ranges from 100–600 trees per ha (Crane et al., 2009). In the past, orchards were established at low densities of 40–100 trees per ha (16 m × 16 m or 10 m × 10 m), and yielded from 4 to 9 t per ha (Mullins, 1987; Oosthuyse 1993a; Fivaz and Stassen, 1997). Interest in high-density plantings commenced in the early 1970s, although commercial low-density plantings remain prevalent (Gunjate, 2009; Gunjate et al., 2009). High-density orchards are probably still considered experimental (Oosthuyse, 2009).

There have been several studies investigating the effect of planting density on the performance of mango trees growing in India, and a few studies in Australia, South Africa and Brazil. There has been no standardization in the range of planting densities investigated, with some authors examining moderate densities up to 800 trees per ha, and other authors examining very high densities up to 3600 trees per ha. Only a few authors report on the growth and yield of the trees over several years. Some researchers have pruned the trees on a regular basis, others have carried out little canopy management, and others have not recorded whether the trees were pruned (Table 2). Most of the authors did not provide information on the rootstocks used.

We provide an overview of some of the work conducted to examine the productivity of high-density mango orchards. First, we examined the performance of trees grown in hedgerows or trellises in northern Australia. Second, we compared the yields of trees grown at low- and high-planting densities, or grown at a range of plant densities. In some of these experiments, planting density was varied by varying the layout of the orchards. Third, we analysed data collected from commercial orchards grown at different tree spacings. Finally, we examined whether methods to control the growth of trees have been successful in the management of high-density orchards.

Two experiments were conducted in Western Australia about 15–20 years ago to examine the effect of planting systems on the productivity of mango orchards. The results of these studies indicate that trees growing at high density can be quite productive at least in the short-term. Müller (1991) established an orchard using 13 cultivars grown at a density of 666 trees per ha in hedgerows, while in a second experiment Johnson and Robinson (2000) grew three cultivars on Tatura trellises at 100, 476, 666 or 1666 trees per ha. In the first study, yields ranged from 3.9 to 9.3 t per ha two years after planting, with the trees not pruned at this stage, and no information provided on the rootstocks used. Müller (1991) suggested that the better cultivars would be highly profitable if planted at 666 trees per ha, however, the long-term sustainability of these plantings is unknown since no further data were published from the experiment.

In the study of Johnson and Robinson (2000), the trees were trained to a trellis for the first four years after planting, and pruned annually to maintain their shape. There was a heavy pruning in year eight, which affected subsequent production. The optimum planting density in terms of cumulative yields per area over nine cropping cycles varied across the three cultivars (Table 1). Intensive canopy management was required to keep the trees productive. No information was provided on the costs of the trellises and the regulator pruning. The experiments in Australia highlight the difficulty in managing mango trees growing at high densities over the long-term.

Some of the studies on high-density plantings have been fairly simple with a comparison of orchards growing at two, three or four different tree densities (Ram and Sirohi, 1988, 1991; Ram et al., 1997, 2001; Reddy et al., 2002; Nath et al., 2007; Krishna et al., 2009; Joglekar et al., 2013; Kumar et al., 2014). High-density orchards were generally more productive than low-density orchards, but the optimum planting density varied across the different experiments (Table 2). Most of the studies did not indicate the rootstock used or if the trees were pruned.

Krishna et al. (2009) provided information on productivity of three cultivars growing in Maharashtra planted at 222 or 494 trees per ha. The trees were seven-years-old at the start of the experiment, with data collected for the subsequent three years. Joglekar et al. (2013) investigated the performance of 'Kesar' growing in the same area planted at 500 or 1000 trees per ha. In the first study, average tree canopy volume (127 and 82 m^3) and yield per tree (21.1 and 18.3 kg) were lower in the close plots than in the open plots, while yield per ha (6.0 and 9.0 t) was higher (Krishna et al., 2009). In the second experiment, average yields per tree between the fifth and the seventh year after planting were similar in the two plots (18 and 17 kg per tree), whereas average yields per area were higher in the close plots (1.8 and 8.5 t per ha) (Joglekar et al., 2013). The trees were pruned to maintain the structure of the canopy, with paclobutrazol also applied. The height of the trees was maintained at 2–3 m. In these two studies, the cost benefit of increased yields versus the expense of establishing and maintaining the high-density orchard was not discussed.

In similar experiments, Ram et al. (2001) found that yield per tree determined in year 14 decreased with planting density, whereas yield per area increased (Fig. 8). These responses were associated with a decrease in the growth of the canopy as planting density increased. Reddy et al. (2002) indicated that tree canopy volume and yield per tree (averaged over three years) tended to decrease with the increase in planting density (Fig. 9). In contrast, yield on an area basis increased, with the maximum yield occurred with 1600 trees per ha. Nath et al. (2007) reported that cumulative yield per tree over ten years decreased with planting density, whereas cumulative yield per area increased up to 1600 trees per ha, with a relatively small difference between 800 and 1600 trees per ha (Fig. 10). These three experiments were terminated prior to the trees reaching their yield potential. The financial implications of the various planting densities were not discussed.

Some researchers have varied planting density by varying the layout of the orchards (Anbu et al., 2001; Singh et al., 2001, 2015; Banik et al., 2013). Typically the trees were planted in a square pattern, hedgerows, double hedgerows, paired rows (pairs of plants) or cluster plantings (two pairs of plants), with the density of the plots ranging from about 100 to about 4000 trees per ha. The age of the trees at the start of the experiments ranged from four- to eight-years old, with data on yield collected for one to six years. None of the authors indicated if the trees were pruned during the experiments. Yield on an area basis increased with planting density, with the highest yield obtained with the double hedgerows in all the studies (Fig. 11). Optimum planting densities ranged from about 200 to about 4000 trees per ha. The productivity of the trees varied with maximum yields ranging from 1.5 to 18 t per ha. It is difficult to recommend optimum planting densities from these investigations.

Oosthuyse (1993a) provided information on the productivity of commercial orchards planted at high densities in South Africa. He found that by year six, 'Tommy Atkins' yielded 19.4, 22.1 and 35.1 t per ha planted at 247, 363 or 550 trees per ha. By year seven, 'Irwin' yielded 16.2, 39.3 and 42.8 t per ha planted at 247, 740 or 1100 trees per ha. It was estimated that there was a net cumulative financial return after five years for the close plantings and after six years for the open plantings. Oosthuyse suggested an optimum planting density of 1100 trees per ha for 'Irwin', however no further data from the orchards have been published. In later work, Oosthuyse (2009) established an ultra-high-density 'Tommy Atkins' orchard planted at 3333 trees per ha in Limpopo Province. He intended to maintain the trees at a height of 2 m and a width of 1 m. Unfortunately, Oosthuyse was unable to control the growth of the trees without reducing production, and the experiment was abandoned.

In northern Australia, Johnson and Robinson (2000) found that productivity in both open (476 trees per ha) and close plots (1666 trees per ha) was relatively low in the first eight years perhaps suggesting over-crowding of the trees (Fig. 12). Fruit production increased in the last year of the experiment in the trees grown in the open plots following a heavy pruning in year eight. Oosthuyse (1993a) indicated that yields per ha of 'Tommy Atkins' over five cropping seasons were higher in plots of 550 trees per ha than plots of 247 trees per ha (Fig. 13). Yields of 'Irwin' were higher in plots of 1100 trees per ha than plots of 247 trees per ha.

Sousa et al. (2012) examined whether pruning and paclobutrazol could control the growth of trees planted at high density. They established a planting of 'Tommy Atkins' in Brazil in 2000 at a density of between 200 and 1400 trees per ha, and collected data on growth and yield in 2007 and 2008. Flowering and fruiting were very poor in 2008, reflecting alternate bearing in the crop. Shoot growth was controlled by regular pruning and the application of paclobutrazol. Tree growth and yield per tree decreased as planting density increased (Fig. 14). Yield on an area basis was best with 357 trees per ha, and was 30% higher than yield of the standard planting at 250 trees per ha. Trees grown at 1000 or 1250 trees per ha were small and had poor crop loads, probably due to over-crowding and shading of the canopy.

Although several studies have examined the relationship between the productivity and planting density in mango orchards, the data collected has been difficult to interpret and optimum planting densities have not been established. The lack of standardisation in experimental planting densities, canopy management

Table 1
Effect of planting density on the performance of three mango cultivars grown in Western Australia. The trees were pruned regularly for the first four years after planting to obtain the required V-shape for a Tatura trellis, and then pruned to maintain this shape. Data on yields were collected for eight or nine years. Adapted from Johnson and Robinson (2000).

Cultivar	Cumulative yield (kg per tree)			Cumulative yield (t per ha)		
	Planting density (trees per ha)			Planting density (trees per ha)		
	476	666	1666	476	666	1666
Kensington Pride	90.5	67.3	20.1	43.1	44.8	33.5
Haden	73.9	37.1	15.2	35.2	24.8	25.7
Magovar	158.5	116.6	44.1	75.4	77.7	75.4

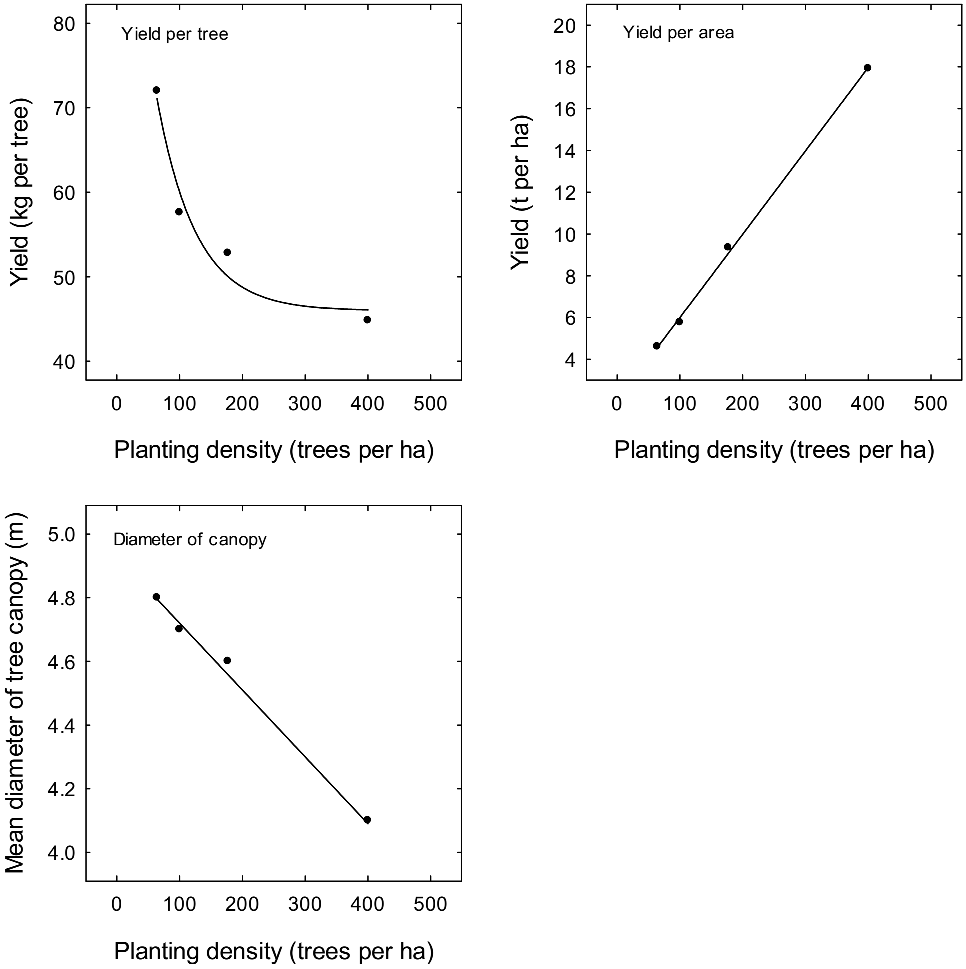

Fig. 8. Effect of planting density on the performance of 'Dashehari' mango trees grown in India. Data collected after 14 years and are adapted from Ram et al. (2001).

techniques and data collection over time makes comparison of the various studies difficult.

An analysis of the responses recorded in the better studies indicates that in nine out of fifteen cases, maximum yields were obtained with the highest planting density used (Table 2). These plantings ranged from about 200–3550 trees per ha. In three out of fifteen cases, maximum yields were similar in the two to three highest densities used. Higher yields were recorded in plantings up to about 700–1600 trees per ha. Finally, there were three out of fifteen cases where an optimum planting density was established. In these experiments, the optimum planting density was about 400–500 trees per ha. Most researchers have not determined whether the costs of additional trees in very dense plantings are justified.

Future research should examine densities up to about 800 trees per ha. A standard system of canopy management needs to be included in the maintenance of the orchards. It is probably best to avoid the use of paclobutrazol, with possible problems with the long-term use of this chemical (see later section). The inclusion of dwarfing scions or rootstocks would assist canopy management and the long-term productivity of the orchards.

6. Use of pruning to control tree growth

Mango trees typically grow into large specimens, up to 10 m or more. When the trees are planted closely together, they usually grow into each other and shade large sections of the lower canopy. Productivity often declines at this stage, normally about ten years after establishment. The development of high-density plantings in mango will require effective strategies to control the growth of the trees (Oosthuyse, 1995; Yeshitela et al., 2005).

There have been numerous studies which have reported on the effect of pruning on tree physiology, growth, and yield. However, only a few of these studies relate directly to the sustainability of high-density plantings. Most of the research on canopy man-

Table 2
Effect of planting density on the yields of mango trees in various experiments in India, Brazil, Australia and South Africa. The data were adapted from the various sources.

Reference	Country	Cultivar	Rootstock	Age of trees	Trees pruned	Planting densities (trees per ha)	Best yield per ha
Kumar et al. (2014)	India	Amrapali	Not recorded	19 years	Not recorded	1111–2500	Highest planting density
Ram et al. (2001)	India	Dashehari	Un-named seedlings	3–4 years	No	64–400	Highest planting density
Reddy et al. (2002)	India	Amrapali	Not recorded	4–6 years	Not recorded	178–1600	Highest planting density
Nath et al. (2007)	India	Amrapali	Not recorded	4–13 years	Not recorded	177–1600	800 and 1600 trees per ha
Anbu et al. (2001)	India	Neelum	Un-named seedlings	5–6 years	Not recorded	204–453	Highest planting density
Banik et al. (2013)	India	Himsagar	Not recorded	4 years	Not recorded	100–222	Highest planting density
Singh et al. (2001)	India	Amrapali	Not recorded	5–7 years	Not recorded	1600–3556	Highest planting density
Lal et al. (2014)	India	Amrapali	Not recorded	19 years	Not recorded	400–888	Highest planting density
Singh et al. (2015)	India	Dashehari	Not recorded	8–13 years	Not recorded	100–222	Highest planting density
Sousa et al. (2012)	Brazil	Tommy Atkins	Fiapo seedlings	7 years	Not recorded	250–1250	357 trees per ha
Johnson and Robinson (2000)	Australia	Kensington Pride	Not recorded	1–10 years	Yes	100–1666	476 trees per ha
		Haden	Not recorded	1–9 years	Yes	100–1666	476 trees per ha
		Mangovar	Not recorded	1–9 years	Yes	100–1666	476, 666 and 1666 trees per ha
Oosthuyse (1993a)	South Africa	Tommy Atkins	Not recorded	1–6 years	Probably	247–550	Highest planting density
		Irwin	Not recorded	1–7 years	Probably	247–1100	740 and 1100 trees per ha

agement has been conducted in South Africa and India, with some studies in Australia and Central and South America. Some researchers have initiated relatively simple experiments and compared the yields of pruned and unpruned trees. Other workers have undertaken more complex experiments, and have compared the yields of trees pruned using different techniques or at different times of the year. The research has been conducted on both new and old plantings that have become crowded and unproductive. Pruning usually leads to better distribution of light within the tree's canopy. Following pruning, the trees are initially smaller but eventually the canopy recovers. The effect of pruning on productivity depends on the interaction of between improved light distribution and the loss of fruiting wood and leaf area.

We examined the effect of canopy management on the performance of mango trees growing in different environments. Several key issues were analysed, including the relationship between productivity and the architecture of the trees, the different responses of young and old trees to canopy management, the importance of time of pruning, and the relationships between yield, flowering, light interception and pruning.

Stassen et al. (1999) and Avilán et al. (2003) investigated the effect of tree architecture on the performance of mango orchards growing in South Africa and South America, respectively. They were interested in determining whether trees pruned to different shapes were more productive than trees left to grow without canopy management.

In South Africa, the trees trained to a central leader, closed vase or to a palmette were smaller than the trees pruned to other shapes or left unpruned (Fig. 15; Stassen et al., 1999). Accumulated yields from 1995 to 1997 were reduced by pruning compared with the yields of the controls (unpruned), with the trees grown as open vases yielding best in the pruned group. Relative accumulated yields (yields per canopy volume) were best with the trees pruned to a central leader, closed vase or to a palmette. By the end of the experiment, the control trees had filled their allocated space and yields started to decline (Fig. 15). In contrast, the productivity of the trees pruned to an open vase was relatively stable.

In Venezuela, mean yields over two cycles of production were higher in the controls (69 kg per tree), and lower in the trees pruned to a square (53 kg per tree) or to a pyramid (43 kg per tree) (LSD, $P = 0.05$, 10) (Avilán et al., 2003). Yield per unit tree volume declined over the two cycles of production in the controls as they began to shade each other, whereas the efficiency of yield was relatively stable in the pruned plots. Pruning initially improved the distribution of light within the tree but also encouraged strong regrowth of the canopy, which competed with fruit production and delayed the time of flowering. The results of the experiments in South Africa and South America suggest that changes to the architecture of mango tree can reduce yields, at least in the short-term. Heavy pruning encourages excessive re-growth and restricts fruit production, even though light interception in the canopy is initially improved.

Some of the canopy management research has been fairly simple and compared the productivity of trees that were pruned with the productivity of unpruned, control trees. The results of some of the studies from South Africa (Oosthuyse, 1994; Stassen et al., 1999; Oosthuyse, 1997) are discussed here. In the first study, trees were left unpruned or pruned to remove terminal shoots after harvest in January (Oosthuyse, 1994). By early April (a few months before floral initiation), the pruned trees had produced a uniform growth flush, while the unpruned trees were highly variable. Twenty-three percent of the branches in the unpruned trees failed to produce new shoots compared with none in the pruned trees. Ninety-eight percent of the branches flowered in the unpruned trees compared with eighty-six percent in the pruned trees. Yields in the two treatments were not significant ($P > 0.05$) different (57 and 65 kg per tree).

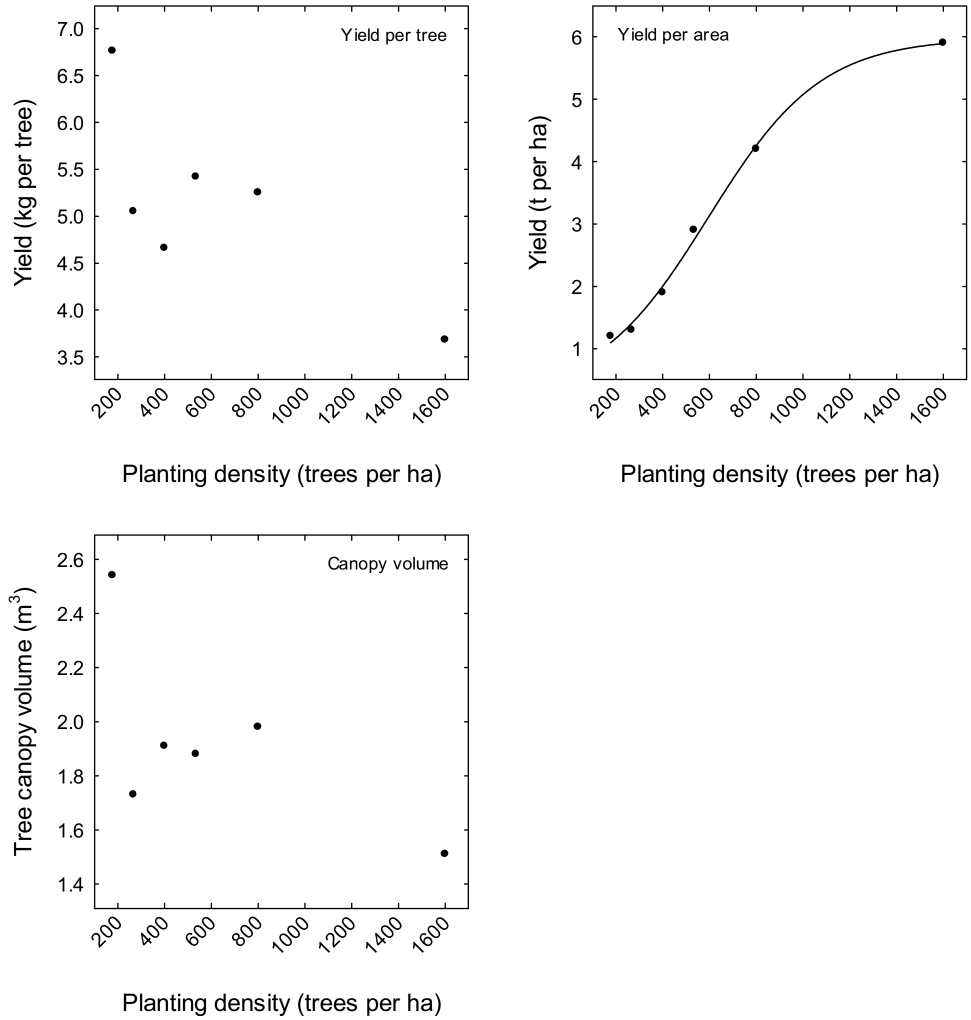

Fig. 9. Effect of planting density on the performance of 'Amrapali' mango trees grown in India. Data on yield are averaged over three years. Data are adapted from Reddy et al. (2002).

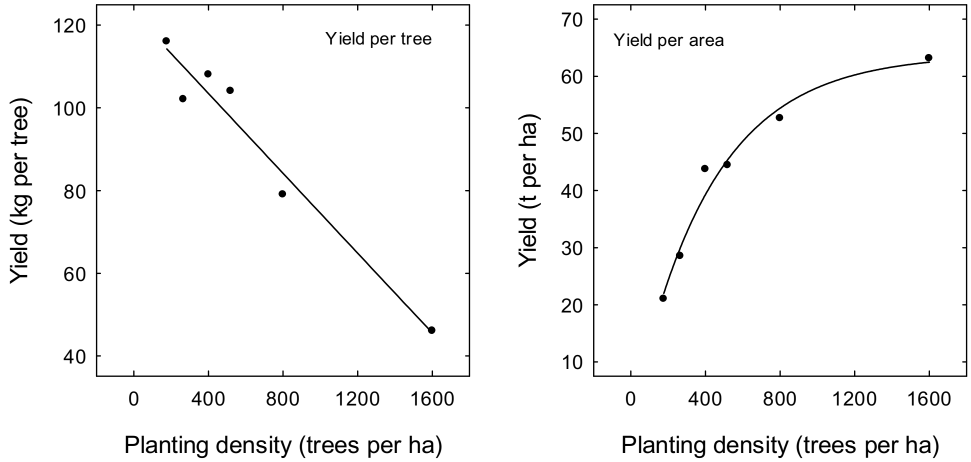

Fig. 10. Effect of planting density on the performance of 'Amrapali' mango trees grown in India. Data on yield are accumulated over ten years and are adapted from Nath et al. (2007).

In the second study in South Africa, cumulative yields over three years were similar in the controls and the trees pruned in October (both with 93 kg per tree) and slightly lower in the trees pruned in November or January (82 and 87 kg per tree) (Stassen et al., 1999). In this environment, the trees flower around September, with the fruit harvested in January and February.

In the third study in South Africa, half the trees were pruned after harvest to remove all the new shoots. Control trees were left unpruned (Oosthuyse, 1997). Pruning reduced yield in 'Tommy

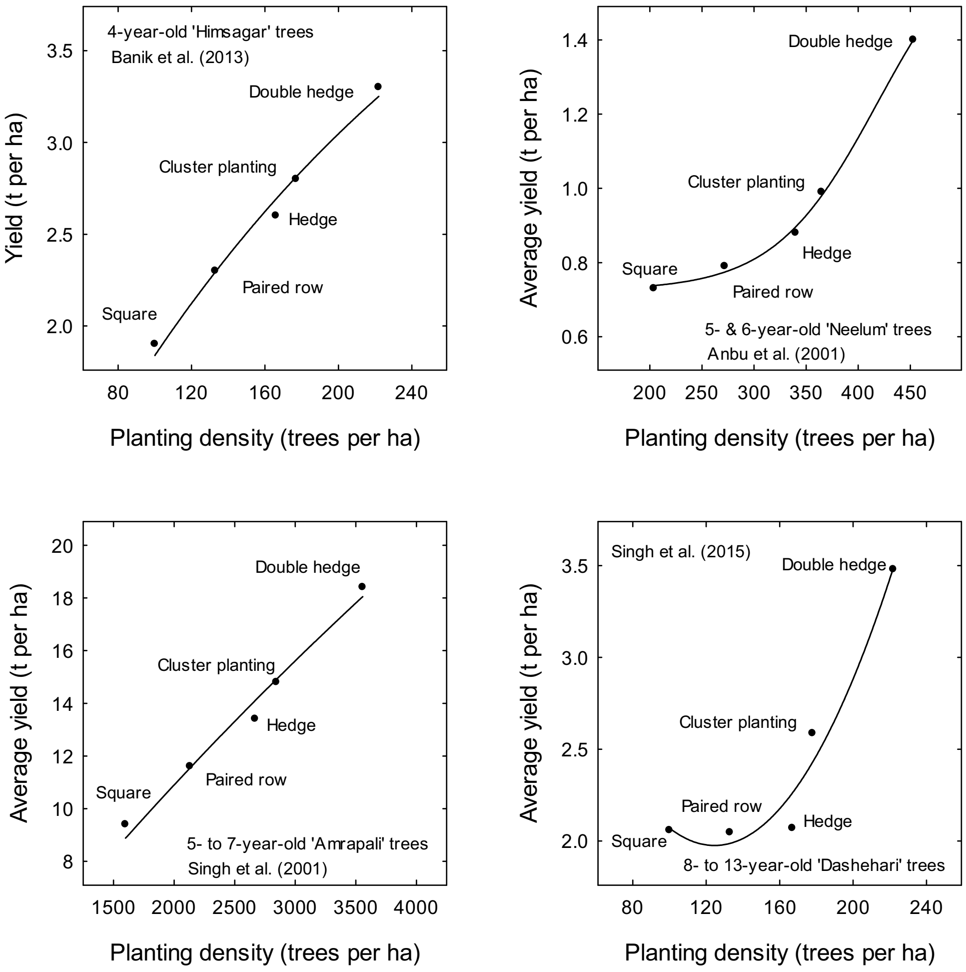

Fig. 11. Effect of planting density and planting system on the productivity of 'Himsagar' (Banik et al., 2013), 'Neelum' (Anbu et al., 2001), 'Amrapali' (Singh et al., 2001) and 'Dashehari' (Singh et al., 2015) mango trees grown in India. Data are adapted from the various sources.

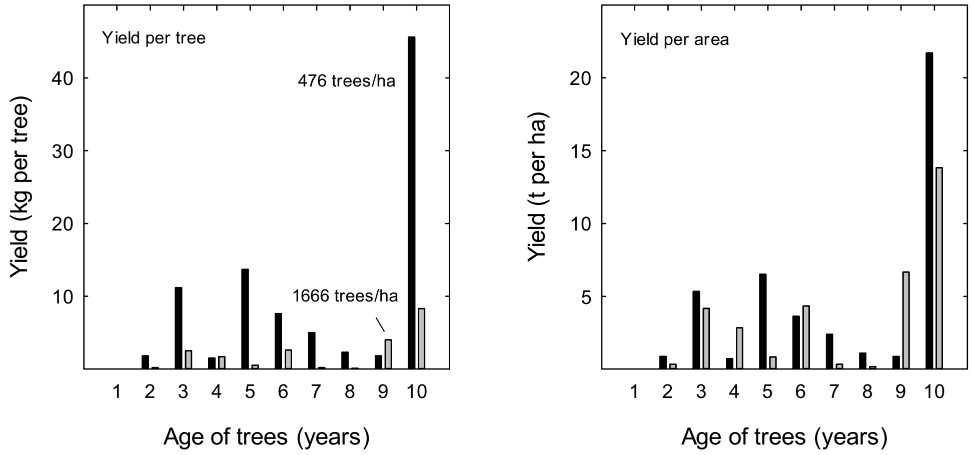

Fig. 12. Effect of planting density on the productivity of 'Kensington Pride' mango trees grown in northern Australia. Data are adapted from Johnson and Robinson (2000).

Atkins', 'Sensation', 'Heidi' and 'Kent' compared with the yield in the controls ($P < 0.05$). Pruning had no effect on yield in 'Zill'. None of the 'Keitt' trees produced a crop (control and pruned plots). Low productivity after pruning in 'Sensation', 'Heidi' and 'Kent' was related to poor flowering. Flowering was typically delayed in the pruned trees suggesting that it was too late for heavy flowering in some of the cultivars. The results of these experiments indicate a mixed effect of pruning on the productivity of mango trees growing in South Africa. The different responses are probably related to the effect of pruning on flower initiation and on the volume of the canopy remaining to support the developing crop.

Several researchers have examined the effect of pruning on the performance of old orchards (Ram et al., 2005; Lal and Mishra, 2007, 2010; Avilán et al., 2008; Reddy and Kurian, 2011; Das and Jana, 2012; Asrey et al., 2013). Some of the investigators cut back the tops and sides of the trees severely, while other investigators used

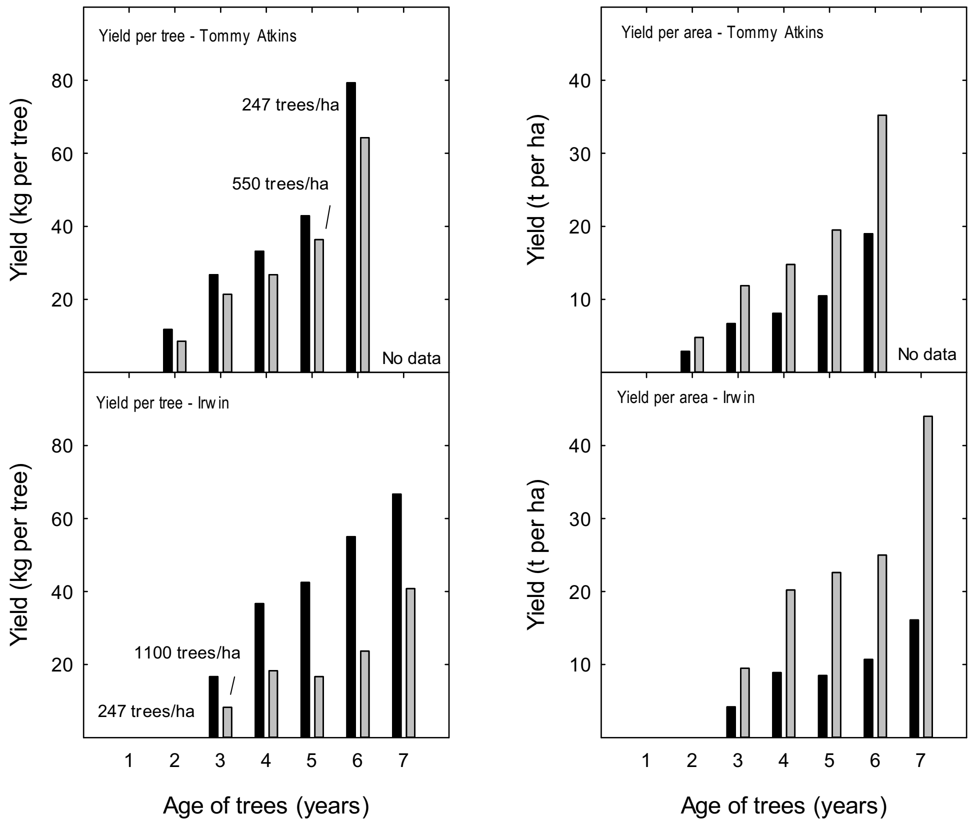

Fig. 13. Effect of planting density on the productivity of 'Tommy Atkins' and 'Irwin' mango trees grown in South Africa. Data are adapted from Oosthuyse (1993a).

a more strategic approach and removed some of the terminal and internal branches to improve the distribution of light through the tree. Examples of the different approaches are presented here. The results of these studies suggest that overall productivity is better with light pruning than with more severe pruning.

Das and Jana (2012) pruned 24-year-old 'Amrapali' trees to reduce the heights of the canopies to 1.0, 1.5 or 2.0 m in December 2005 (before floral induction) in India. The trees did not crop in 2006, 2007 and 2008. Yields in the three treatments were not significantly different in 2009 and 2010 ($P > 0.05$), reflecting large variations in the yields of individual treatments. In an experiment in India, Reddy and Kurian (2011) pruned 26-year-old trees of 'Alphonso' to cut the terminals 30 or 45 cm from their origin on the main branches after harvest in September 2004. There was no flowering or cropping in the pruned trees in 2005. Average yields from 2006 to 2009 were higher in the pruned trees (86 and 80 kg per tree) than in the control trees (47 kg per tree). This response reflected higher yields in the pruned trees than in the control trees in three out of the four experimental years ($P < 0.05$) and similar yields in one out of four experimental years ($P > 0.05$).

Avilán et al. (2008) investigated different pruning strategies on the performance of trees over four years in Venezuela. The trees were pruned 2.5 m above the ground, with some of these trees having laterals pruned at 1.8 m above the ground or some internal branches removed. Sets of unpruned trees were left as control plots. Any form of pruning encouraged vigorous regrowth and reduced yields compared with the control trees (Table 3). The yields of the pruned trees were about 40–50% of that of the controls, with no clear difference between the different pruning strategies. Lal and Mishra (2007, 2010) examined the effect of pruning on the performance of 45-year-old 'Chausa' and 'Mallika' trees in India. Pruning the branches in December reduced the heights of the trees compared with those where the trees were opened up or left unpruned (Table 4). The pruned trees had higher yields than the control trees, with the trees pruned to remove the primary branches slightly better in the pruned group.

Table 3
Effect of pruning on the growth and yield of ten-year-old mango trees planted at 278 trees per ha in Venezuela. The trees were pruned at the top of the canopy (2.5 m above the ground), or pruned at the top of the canopy and lateral branches pruned or internal branches removed. Data are the means of four cultivars pooled over four years. Means in a column followed by different letters are significantly different ($P < 0.05$). Adapted from Avilán et al. (2008).

Treatment	Increase in tree canopy volume (m^3)	Yield (kg per tree)
Control	12.2 a	37.0 b
Tree pruned at 2.5 m above ground	53.5 b	23.3 a
Tree pruned at 2.5 m and laterals pruned at 1.8 m	54.0 b	23.0 a
Trees pruned at 2.5 m and some internal branches removed	53.4 b	19.1 a

The time of pruning can affect the growth and yield of mango, and this is usually related to the impact of flush development on the success of flowering, or changes to the number of inflorescences developing on the terminal branches (Oosthuyse, 1993b; Swaroop et al., 2001; Wilkie et al., 2008).

Swaroop et al. (2001) examined the effect of different times of pruning on the performance of 'Dashehari' trees in India over two seasons. In this environment, floral initiation occurs in February, with the inflorescences emerging in March and April. In the first season, the trees pruned in November had similar crops as the unpruned controls, with heavier crops when the trees were pruned in December and no crop when the trees were pruned in January or February (Fig. 16). In the second season, the trees pruned in July or August had heavier crops than the controls, and the trees pruned in September, November or December had lighter crops than the con-

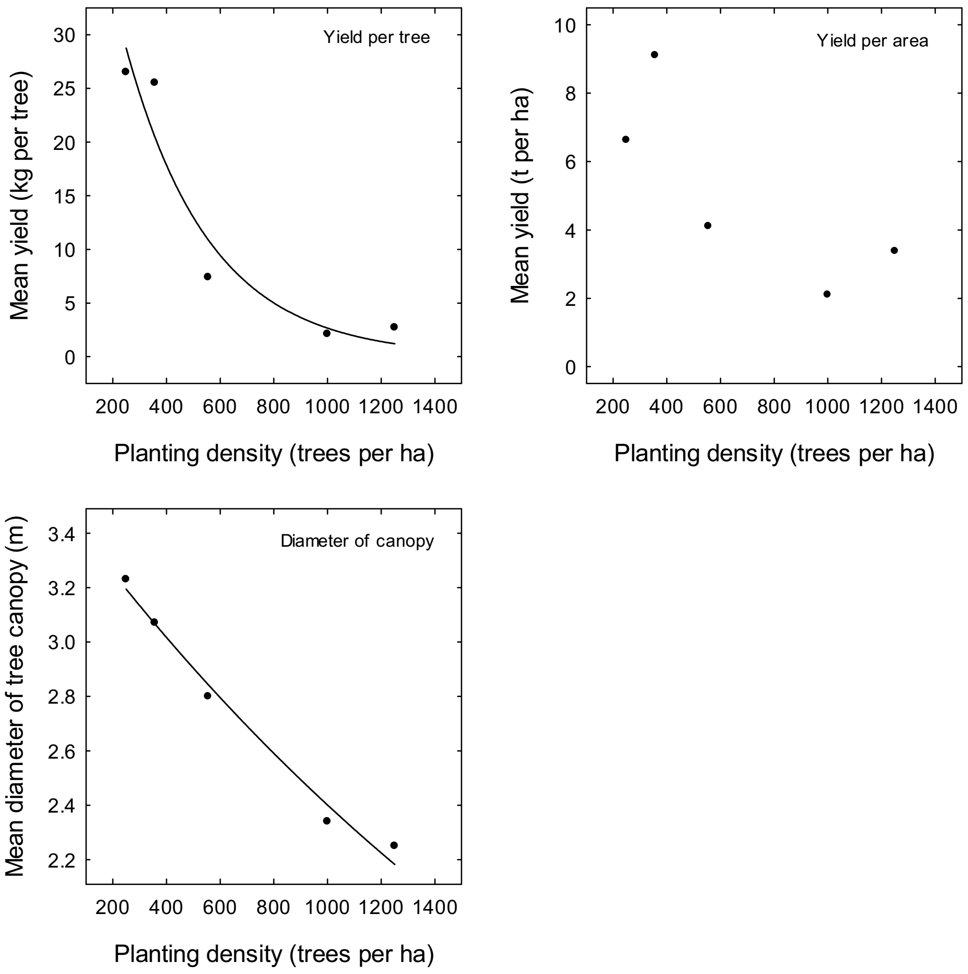

Fig. 14. Effect of planting density on the performance of 'Tommy Atkins' mango trees grown in Brazil. Data are averaged over two years and are adapted from Sousa et al. (2012).

Table 4

Effect of pruning on the growth and yield of two mango cultivars in India. The study was conducted on 45-year-old trees that had become over-crowded and unproductive. The trees were pruned annually. The heights of the trees were recorded after eight years, with average yields over this time also presented. Height means in a column followed by different letters are significantly different ($P < 0.05$). Adapted from Lal and Mishra (2007, 2010).

Treatment	Chauasa		Mallika	
	Height of tree (m)	Yield (kg per tree)	Height of tree (m)	Yield (kg per tree)
Control	6.9 b	58	6.9 b	68
Pruned to remove primary & secondary branches	4.6 a	68	4.8 a	106
Pruned to remove primary branches	4.9 a	79	5.1 a	114
Opening of centre of tree	6.8 b	75	6.7 a	104

trols. Once again the trees pruned in January, February or October had no crops.

In the study in India (Swaroop et al., 2001), there was a strong relationship between yield and the number of inflorescences per shoot (Fig. 17). There appeared to be a cycle of poor and abundant flowering and cropping, depending on the time of pruning, probably related to the impact of pruning on flush development (Malshe and Diwate, 2015). These authors showed that vegetative growth in June had no impact on flowering and yield in India ($r = -0.04$ or 0.01), whereas flushing in September had a negative impact on reproductive growth ($r = -0.61$ or -0.55). The results of the studies by Swaroop et al. (2001) are consistent with later research conducted in Australia by Wilkie et al. (2008). They pruned 'Honey Gold' trees over nine successive weeks from February to April, extending from the time after harvest to before floral induction. Flowering and yield decreased as pruning was delayed after early February.

Oosthuyse (1993b) removed the terminal buds or the developing inflorescences from 'Sensation' trees in early, mid- or late July as the trees were flowering in South Africa. Control trees were left unpruned. The trees pruned in early or mid-July had lower yields (26 kg per tree) than the controls (44 kg per tree) ($P < 0.05$), while the trees pruned in late July had similar yields as the controls (34 kg per tree) ($P > 0.05$). The pruned trees had several inflorescences on each shoot and this possibly increased competition between the developing fruitlets and reduced the yields.

Pruning can increase the distribution of light through the tree's canopy and increase leaf photosynthesis, but can also decrease the leaf area supporting the developing crop (Schaffer and Gaye, 1989a,b; Pratap et al., 2003; Shinde et al., 2003; Sharma et al., 2006). Sometimes the effects on tree physiology are short-lived, with new

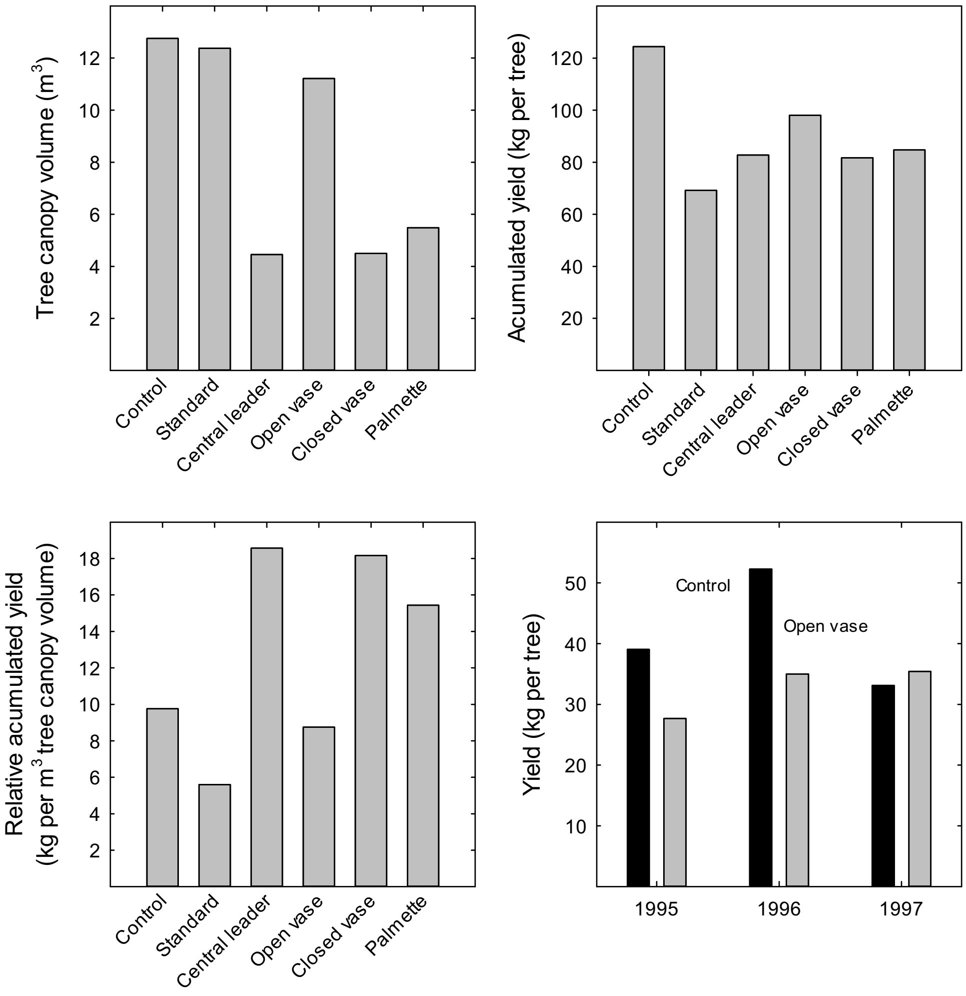

Fig. 15. Effect of tree architecture on the performance of 'Sensation' mango trees grown in South Africa. Data are adapted from Stassen et al. (1999).

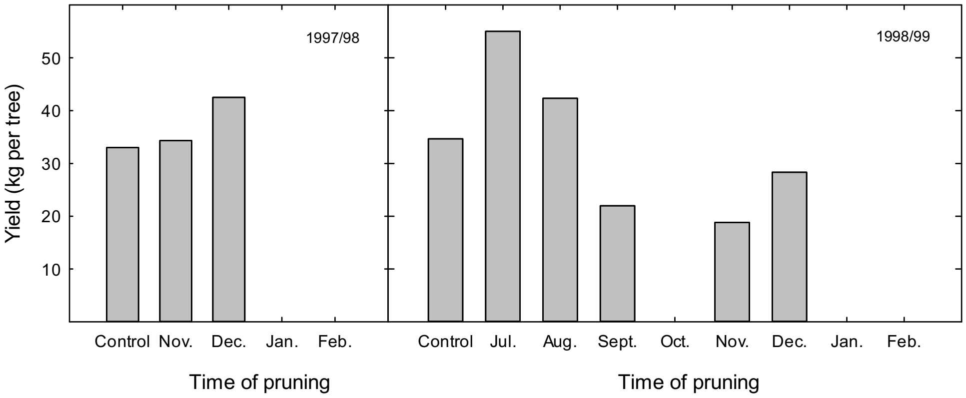

Fig. 16. Effect of the time of pruning on the productivity of 'Dashehari' mango trees grown in India. Data are adapted from Swaroop et al. (2001).

growth produced after pruning eventually shading the older leaves. Examples of the different responses are provided below.

Shinde et al. (2003) studied the relationship between productivity and light in 35-year-old 'Alphonso' trees growing in India. The trees were pruned lightly by cutting back alternate limbs or all the limbs on the trees by 50 cm, or by opening the centres of the trees and thinning some branches after harvest. Pruning increased light interception inside the canopy compared with values recorded for the control trees, but had no significant effect on fruit production (Table 5). In related studies, Pratap et al. (2003) removed 10, 20 or 30 cm from the terminal branches across the entire canopy of 14-year-old 'Amrapali' trees growing in New Delhi. Pruning increased the interception of light in the canopy and net CO_2 assimilation compared with values in the controls (Table 6). Pruning also increased yield, with the trees pruned by removing 20 cm of growth the most productive. In this experiment, the moderate treatment appeared to have increased light interception and photosynthesis without removing too much of the canopy.

Schaffer and Gaye (1989b) studied the effect of pruning on the distribution of light within the canopies of trees growing in Florida.

Table 5
Effect of pruning on the performance of 35-year-old 'Alphonso' mango trees planted at 100 trees per ha in India. The trees were pruned after harvest to remove 50 cm from alternate shoots or all the terminal shoots, or by opening of the centre of the tree and thinning of branches. Data on light interception were recorded after three years. Data on yield are means over three years. Yield means in a column followed by different letters are significantly different ($P < 0.05$). Adapted from Shinde et al. (2003).

Treatment	Light level 1 m above the tree's crotch (% of full sun)	Light level 2 m above the tree's crotch (% of full sun)	Yield (kg per tree)
Control	14.9	25.6	13.5 a
Heading back of shoots on alternate limbs	40.6	76.7	21.5 a
Heading back of shoots on all limbs	33.5	69.6	10.8 a
Opening of centre of tree and thinning of branches	47.5	70.7	25.0 a

Table 6
Effect of pruning on the performance of 14-year-old 'Amrapali' mango trees planted at 1600 trees per ha in India. The trees were pruned in July after harvest to remove 10, 20 or 30 cm from the terminal shoots (light, moderate and severe pruning). Data are means over two years. Means in a column followed by different letters are significantly different ($P < 0.05$). Adapted from Pratap et al. (2003).

Treatment	Light level 1–2 m above the tree's crotch (% of control)	Net CO_2 assimilation (μmol per m^2 s^{-1})	Yield (kg per tree)
Control	100 a	4.0 a	13.9 a
Light pruning	110 a	5.9 b	18.1 b
Moderate pruning	125 b	5.9 b	22.6 c
Severe pruning	132 b	4.8 a	18.0 b

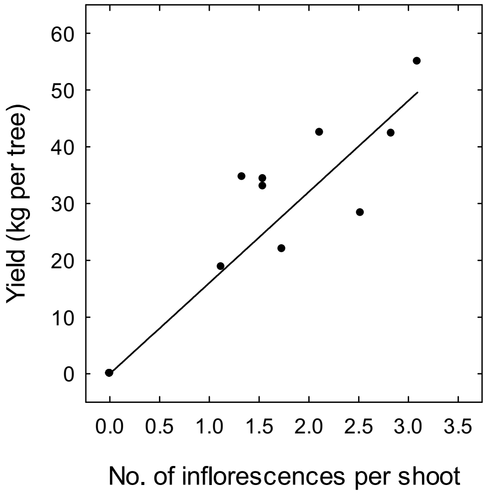

Fig. 17. Relationship between yield and flowering after pruning of 'Dashehari' mango trees growing in India. The trees were pruned from November to February in 1997/98 (N = 5), and from July to February in 1998/99 (N = 9). Control trees were left unpruned. There was a strong relationship between yield and the incidence of flowering ($R^2 = 0.86$). Data are adapted from Swaroop et al. (2001).

The trees were pruned in March around flower opening to remove about a quarter of the centre of the canopy. Other trees were left unpruned as control plots. Vegetative regrowth in the pruned trees was removed regularly over the next six months. Information was collected on photosynthetic photon flux levels 0–1 m above the ground and 1–2 m above the ground under overcast conditions. Data were collected in April (around fruit set), July (around harvest) and November (before floral induction). Light penetration within the pruned trees was on average around 25% during each of the measurement periods. In contrast, light penetration in control trees averaged 10–15% in April and July, and 5% in November. Lower light levels in the control trees were due to increased shading due to vegetative growth produced from March to November. Unfortunately no yield data were collected during this study.

Medina-Urrutia and Nuñez-Elisea (1997) examined the effect of hedging on the performance of eight-year-old trees of 'Tommy Atkins'. The pruned trees had lower average yields (153–188 kg per tree) than the control trees (261 kg per tree). They also had smaller canopies (104–136 m^3 versus 317 m^3) than the control trees ($P < 0.05$). In other work, Cruz-Barrón et al. (2014) pruned trees of 'Ataulfo' in 2007, 2008 and 2009, or only in 2007 and 2009. Pruning involved reducing the radius of the canopy to between 1.8 and 2.0 m and the height of the canopy to 4.5 m. There were no sets of unpruned, control trees. The average increase in shoot dry weight (branches and leaves) was 18 kg per tree with annual pruning and 34 kg per tree with biennial pruning. Shoot dry weights were lower with annual pruning than with biennial pruning in two out of two years of data collection ($P < 0.05$). Average yields were lower with annual (47 kg per tree) than with biennial pruning (95 kg per tree) ($P < 0.05$). In these two experiments in Mexico, pruning appears to have increased the distribution of light within the tree, but possibly reduced total canopy photosynthesis. Pruning produced smaller trees and lower yields.

There has been considerable work undertaken on the effect of pruning on the performance of mango. Researchers have investigated the effect of pruning on young trees, on mature trees that were relatively productive, and on old trees that were crowded and unproductive. A range of different strategies has been employed, with Horticulturists examining the effect of the severity, timing and frequency of pruning. Some workers have examined the effect of pruning on the distribution of light through the canopy and the effect of tree architecture on productivity. There have been few experiments examining the long-term benefits of pruning on the productivity of trees. Many of the experiments ran for only a single season, or at best two or three seasons. It is difficult to see how the results of much of the research might apply directly to the management of high-density plantings.

There has been a large variation in the response of mango trees to canopy management. In some instances, pruning increased production, while in other cases, pruning decreased production or had little effect on production. The benefits of pruning were sometimes short-lived, with pruning stimulating vegetative regrowth at the expense of fruiting. This problem has been noted in other crops such as olive (Cherbiy-Hoffmann et al., 2012). These authors showed that oil production in hedgerows is limited by low solar radiation within the canopy, and that substantial vegetative growth triggered by pruning can reduce average light interception and reduce productivity.

Overall yields in mango tended to be higher with light or moderate pruning than with heavy pruning. Heavy pruning often inhibited fruit production for several seasons. This has occurred when old unproductive trees have been rejuvenated. Light pruning involved removing part of the outer canopy, whereas heavy pruning involved reducing the height of the tree by a metre or more. Differences in the responses recorded in the various experiments are related to the effect of canopy management on light interception,

Table 7
Effect of paclobutrazol on shoot growth and yield of 'Alphonso' mango trees growing in India. Paclobutrazol was applied to the foliage or as a soil drench in July or August each year. Data on shoot growth and yield have been pooled over three years. Means in a column followed by different letters are significantly different ($P < 0.05$). Adapted from Burondkar and Gunjate (1993).

Treatment	Length of shoot (cm)	Percentage of shoots flowering	Yield (kg per tree)
Control	19.7 d	34.2 a	25.2 a
Foliar paclobutrazol (0.5 g per L)	18.8 cd	38.4 a	25.2 a
Foliar paclobutrazol (1.0 g per L)	15.5 bc	61.8 b	46.5 bc
Foliar paclobutrazol (2.0 g per L)	12.9 ab	55.8 b	35.6 ab
Soil paclobutrazol (5 g per tree)	12.2 ab	82.3 c	63.9 cd
Soil paclobutrazol (10 g per tree)	11.3 a	85.9 c	71.0 d

gas exchange, the leaf area supporting the crop and on the success of flowering. In other crops such as olive, effective canopy management involved removal of selected branches as well as topping to maximize light penetration throughout the hedgerows (Tombesi and Farinelli, 2014). Yields often decrease with the intensity of pruning. In one study in olive, yields were highest in the control trees, intermediate when the trees were pruned to remove the lower canopy, and lowest when the trees were pruned to remove the lower canopy and hedged (Tombesi et al., 2014). In another study in macadamia, fully-topped trees reduced yields by 70% over two years compared with the yields of control, unpruned trees, while the yields of half-topped trees were reduced by 7% (Olesen et al., 2016). These results suggests that a loss of leaf area supporting the crop, the loss of potential fruiting sites and regrowth after pruning can be problematic in mango and other tree crops.

Pruning typically improves the interception of light by the lower sections of the tree. Sometimes, pruning can promote excessive shoot growth or shoot growth at the wrong time, which can inhibit flowering and fruit set. Pruning can reduce the size of the canopy supporting the developing crop.

There is some evidence that the timing of pruning can affect the yield of the trees. Work in eastern Australia showed that flowering and yield decreased as pruning was delayed after early February (Wilkie et al., 2008). Other studies in India indicated better flowering when the trees were pruning at certain times of the growth cycle (Swaroop et al., 2001). Only limited information is available on the optimum tree shape for mango. Research in South Africa indicated that trees pruned to an open vase were more productive than trees pruned to other shapes, although they all had lower yields than unpruned, control trees. Other studies in Mexico showed no clear differences in yield when the tops of the trees were pruned at different angles (Medina-Urrutia and Nuñez-Elisea, 1997). To summarize, pruning can have a variable effect on potential productivity, depending on its effect on light levels, regrowth, canopy photosynthesis and flowering. Production is usually best following light pruning. The timing of canopy management must take into account the annual flowering cycle of the trees.

7. Use of growth regulators to control tree size

Growth regulators have been used since the 1980s to improve the productivity of commercial mango orchards. Most of the research has involved the effect of the triazole, paclobutrazol, which has been registered for use in many countries (Yadava and Singh, 1998; Saran et al., 2008; Hasan et al., 2013; Shinde et al., 2015). Other growth regulators such as uniconazole and prohexadione-Ca have also been evaluated (Silva et al., 2010, 2013; Mouco et al., 2013). These chemicals affect many aspects of plant growth and development, and typically reduce the concentration of gibberellins in plant tissues (Burondkar et al., 2016).

Paclobutrazol decreases shoot extension and the number of shoot flushes per tree, and produces smaller tree canopies (Kulkarni, 1988; González and Blaikie, 2003; Blaikie et al., 2004; Kotur, 2012; Oliveira et al., 2015). Flowering and fruit production are promoted, depending on the dose of the chemical, tree agronomy and the weather (Kurian and Iyer, 1993a,b,c; Burondkar et al., 1997, 2013; Blaikie et al., 2004; Bithell et al., 2013; Hasan et al., 2013; Salvi et al., 2013; García de Niz et al., 2014; Narvariya et al., 2014; Shankaraswamy and Neelavathi, 2016). An analysis of production in Maharashtra in India indicated that the financial returns were more than 150% higher using paclobutrazol compared with standard growing practices (Talathi et al., 2015).

Paclobutrazol reduces the size of the leaves, and increases the concentration of chlorophyll and the activities of anti-oxidative enzymes in these tissues. This growth regulator also increases the concentration of stored carbohydrates in the plant, and alters the sink-source balance of the shoot to favour the fruit (Kurian et al., 2001; González and Blaikie, 2003; Kotur, 2012; Saxena et al., 2014; Upreti et al., 2014; Muengkaew and Chaiprasart, 2016).

Research on the use of paclobutrazol in mango orchards is extensive, with many experiments conducted in India, Mexico, Brazil, Thailand, Australia and elsewhere. The earlier studies examined the response of young plants grown in containers. Later work investigated the effect of the growth regulator in mature orchards. There have also been attempts to determine whether paclobutrazol can be used to restore production in old orchards that have become crowded and unproductive. Other research has assessed the movement, persistence and degradation of the growth regulator in mango trees and soil. There have only been a few studies examining the use of the chemical in trees grown at close spacings.

Details are provided on key responses of mango trees following the application of paclobutrazol. These include the effect of the chemical on shoot growth, flowering and yield (Burondkar and Gunjate, 1993; Yeshitela et al., 2004a; Reddy and Kurian, 2008; Nafees et al., 2010; Reddy et al., 2014; Srilatha et al., 2015). The data collected by these authors was analysed to determine the relationships between yield, flowering and shoot growth after application of the growth regulator. This analysis showed that paclobutrazol usually decreased shoot elongation, increased the percentage of branches flowering and increased fruit yield.

Burondkar and Gunjate (1993) applied paclobutrazol as a foliar spray (0.5, 1.0 or 2.0 g per L) or soil drench (5 or 10 g per tree) to 16-year-old trees growing in India. The chemical was applied in July or August over three years, with data on growth and yield collected over the same period. Yeshitela et al. (2004a) applied paclobutrazol as a foliar spray or as a soil drench (0, 2.75, 5.5, or 8.25 g per tree) to ten-year-old trees growing in Ethiopia. The chemical was applied in August 2002, with data collected on growth and yield in 2003. Nafees et al. (2010) applied paclobutrazol as a soil drench (0, 2, 4, 6, 8, 10 or 12 g per tree) to 20-year-old trees growing in Pakistan in September 2003. Information was collected on shoot extension, tree canopy volume and yield over the next two seasons, with 2004 considered an off-year and 2005 considered an on-year. Reddy et al. (2014) applied paclobutrazol as a soil drench (2.5 or 5.0 g per tree) to 22-year-old trees over five years in India. The chemical was applied in July, August, September or October. Information was collected on flowering and yield.

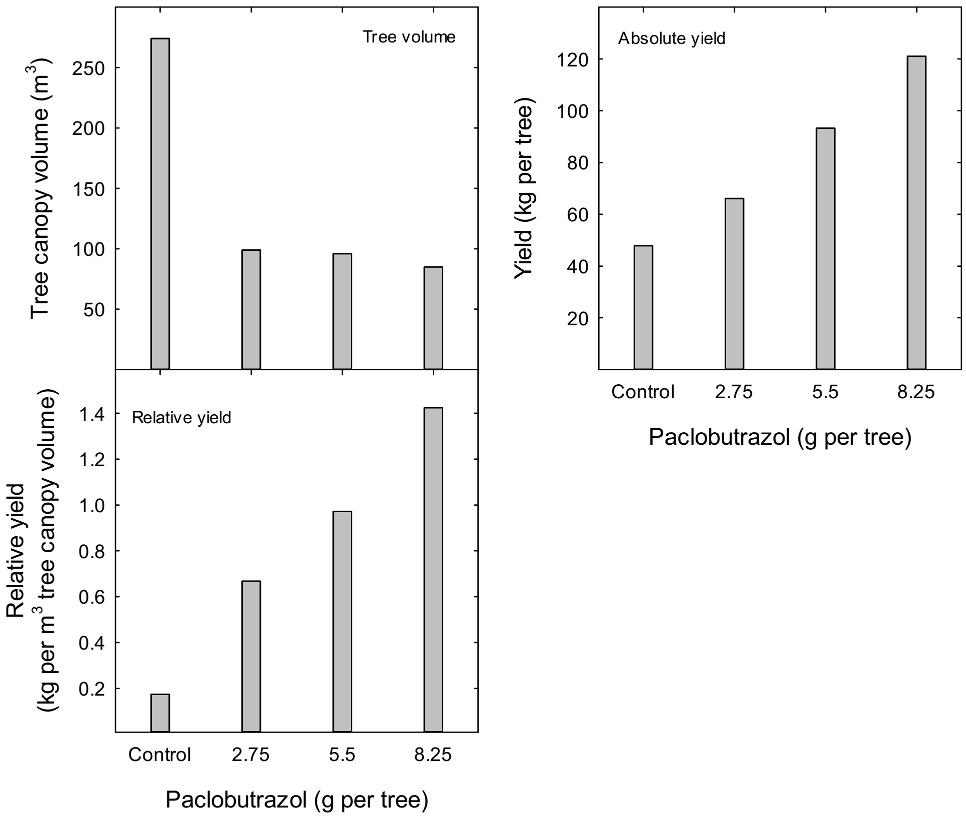

Fig. 18. Effect of paclobutrazol on the performance of 'Tommy Atkins' mango trees grown in Ethiopia. Data are adapted from Yeshitela et al. (2004a).

Burondkar and Gunjate (1993) found that the response to paclobutrazol was greater with soil than with foliar applications (Table 7). The two highest foliar sprays and both soil drenches decreased shoot extension compared with extension in the controls, and increased the number of shoots flowering. Paclobutrazol had a mixed response on fruit production. Yield was increased by the intermediate foliar rate and by both soil rates. Yeshitela et al. (2004a) found that paclobutrazol decreased tree canopy volume after 12 months compared with the controls, with no difference amongst the different rates of application (Fig. 18). In contrast, absolute and relative yields increased with increasing rates of application of the growth regulator. Nafees et al. (2010) found that shoot extension, leaf production and tree canopy volume decreased with increasing dose of paclobutrazol (Fig. 19). Absolute yield increased up to about 10 g of paclobutrazol per tree and then declined slightly. In contrast, relative yield increased with increasing applications of the growth regulator. Paclobutrazol increased the percentage of shoots that flowered. Reddy et al. (2014) found that trees treated with paclobutrazol had higher yields than the controls, with average yields across the five years of 123 kg and 91 kg in the treated and untreated trees, respectively. Overall there was no consistent response to the dose or time of application of the growth regulator.

The results of these studies have shown that there was a strong relationship between yield and flowering (Figs. 20–23). Heavy flowering was associated with heavier yields. In three of these experiments, the author included data on shoot growth which allowed an analysis of the relationship between productivity and vegetative growth. In two of the experiments, there was a negative relationship between yield and shoot growth (Burondkar and Gunjate, 1993; Nafees et al., 2010; Figs. 20 and 22). Heavier yields were associated with smaller shoots. In one of the experiments, there was no clear relationship between yield and canopy volume (Yeshitela et al., 2004a; Fig. 21). The results of these experiments indicate that higher yields after the application of paclobutrazol was associated with better flowering and sometimes a reduction in shoot growth. Shorter shoots and smaller canopies would assist canopy management in high-density plantings.

Paclobutrazol has a long life in mango trees and soils, and it is important to consider the residual effect of the growth regulator on the productivity of orchards (Salazar-García and Vasquez-Valdivia, 1997; Reddy and Kurian, 2008).

Salazar-García and Vasquez-Valdivia (1997) applied paclobutrazol in June 1990, and collected data on the performance of the trees in 1991, 1992 and 1993. Paclobutrazol was applied at rates from 0 to 40 g per tree. The response of the trees to the higher rates of 10–40 g per tree is shown in Table 8. They found that shoot elongation was reduced by the growth regulator applied at 10 g per tree or above (Table 8). Paclobutrazol at this concentration was effective for one year, paclobutrazol at 15 or 20 g per tree was effective for two years, while paclobutrazol at 40 g per tree was effective for three years. There was a mixed effect on fruit production when yield was expressed per unit of tree canopy surface area (Table 8). Trees given from 2.5 to 20 g of paclobutrazol had similar relative yields as the controls (data for 2.5 and 5.0 g per tree not shown in Table 8). Trees given 40 g of paclobutrazol had lower relative yields than the controls in the first year, similar relative yields in the second year, and higher relative yields in the third year (Salazar-García and Vasquez-Valdivia, 1997).

In the second experiment, Reddy and Kurian (2008) applied paclobutrazol in September 1996, 1997 and 1998, and collected data on the performance of the trees from 1997 to 2002. They observed that paclobutrazol decreased shoot elongation and increased yield for a year after the last application of the chemical (Fig. 24). Average yields were 50 kg per tree in the treated plots and 25 kg per tree in the control plots. In these studies, paclobutrazol inhibited shoot growth and increased yield for a year after the last

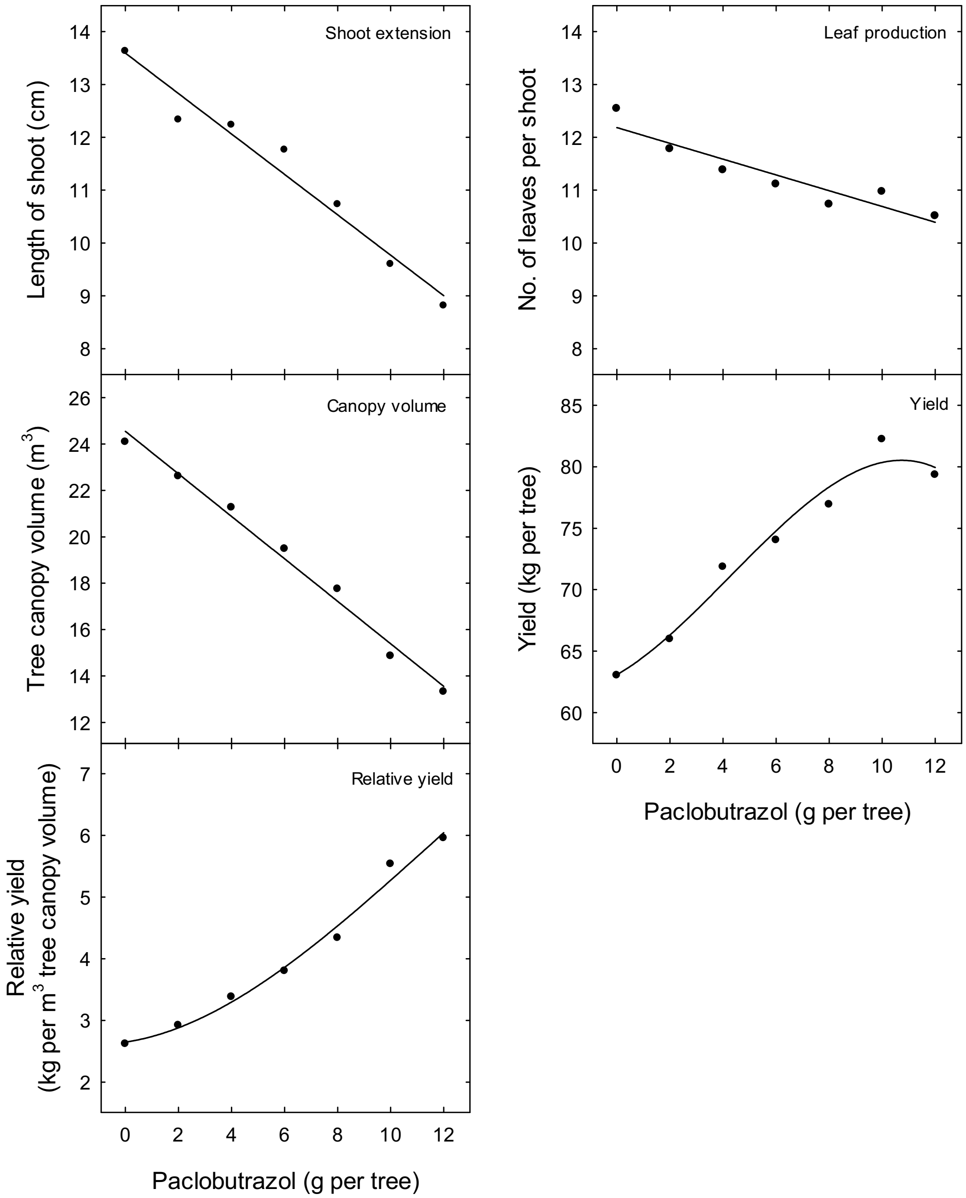

Fig. 19. Effect of paclobutrazol on the performance of 'Chaunsa', 'Dashehari' and 'Anwar Ratool' mango trees grown in India. Data have been pooled across the three cultivars and are adapted from Nafees et al. (2010).

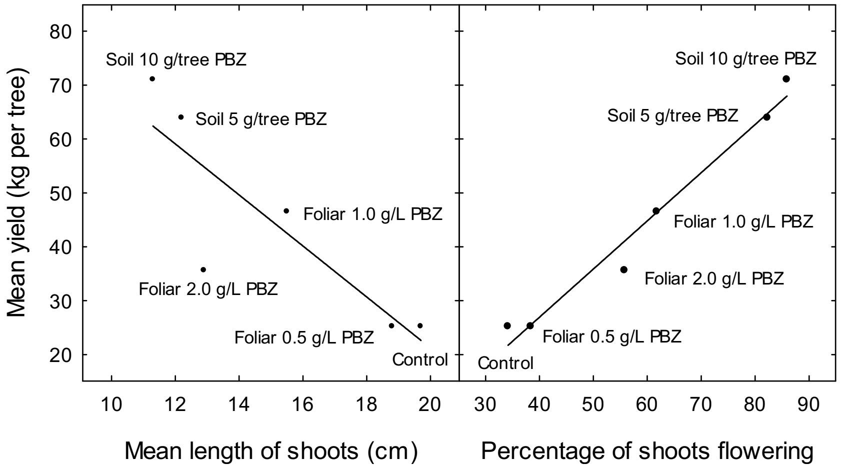

Fig. 20. Relationship between yield, shoot growth and flowering in 'Alphonso' mango trees given paclobutrazol in India. There were three rates of foliar-applied paclobutrazol (0.5, 1.0 and 2.0 g per L), two rates of soil-applied paclobutrazol (5 and 10 g per tree) and control plots (N = 6). Data are the means of three years and are adapted from Burondkar and Gunjate (1993).

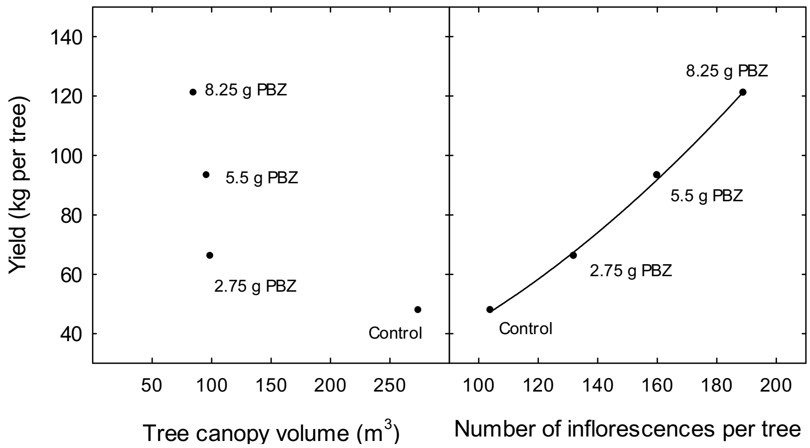

Fig. 21. Relationship between yield, and shoot growth and flowering in 'Tommy Atkins' mango trees given paclobutrazol in Ethiopia. There were three rates of paclobutrazol (2.75, 5.5 and 8.25 g per tree) and control plots (N = 4). Data are adapted from Yeshitela et al. (2004a).

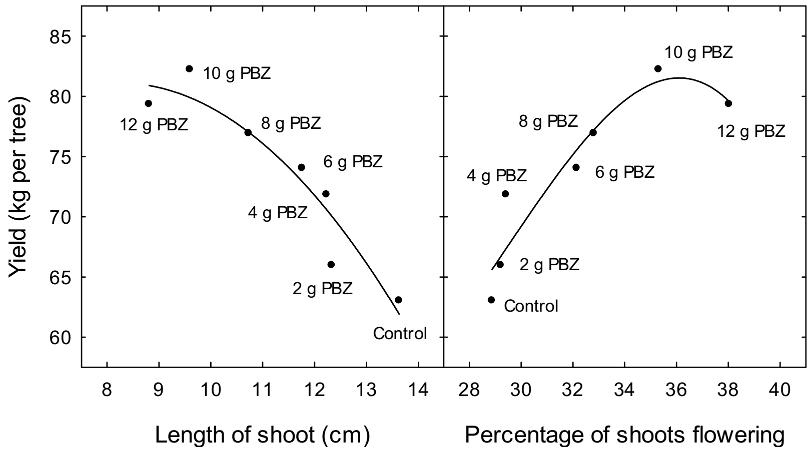

Fig. 22. Relationship between yield, shoot growth and flowering in 'Chaunsa', 'Dashehari' and 'Anwar Ratool' mango trees given paclobutrazol in India. There were six rates of paclobutrazol (2, 4, 6, 8, 10 and 12 g per tree) and control plots (N = 7). Data have been pooled across the three cultivars and are adapted from Nafees et al. (2010).

Table 8

Effect of paclobutrazol on shoot growth and relative yield in 'Tommy Atkins' mango trees growing in Mexico. A single application of the growth regulator was made in 1990, and growth and yield recorded over three years. Year means in a column followed by different letters are significantly different ($P < 0.05$). Adapted from Salazar-García and Vasquez-Valdivia (1997).

Paclobutrazol (g per tree)	Length of shoot (cm)			No. fruit per m^2 of tree canopy surface area			
	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3	Total
0	21.9 c	21.7 b	26.5 b	5.1 b	17.4 ab	15.1 a	37.6
10	11.7 b	18.2 b	27.8 b	5.4 b	18.5 ab	13.0 a	36.9
15	6.9 ab	7.0 a	26.7 b	3.8 b	20.0 b	12.5 a	36.3
20	3.7 a	5.9 a	22.8 b	5.0 b	18.3 ab	11.3 a	34.6
40	1.2 a	1.0 a	16.5 a	2.6 a	15.7 a	19.0 b	37.3

application suggesting a long residual life of the chemical in the orchard.

Several workers have investigated the effectiveness of different methods of applying paclobutrazol. The chemical can be applied as a foliar spray, injected into the trunk of the tree or applied as a drench to the soil. Generally, soil drenches were more effective in inhibiting tree growth and/or increasing yields than foliar sprays or trunk injections (Winston, 1992; Yeshitela et al., 2004a,b; Reddy and Kurian, 2008).

There has been limited research on the use of paclobutrazol in the management of close plantings of mango (Kulkarni and Hamilton, 1997; Avilán et al., 2008; Srilatha et al., 2015). These authors were interested in determining whether the growth regulator could maintain production in trees that had been pruned.

In the first study (Kulkarni and Hamilton, 1997), the orchard was planted out at 200 trees per ha. Trees that were pruned and given paclobutrazol had higher accumulated yields (145 kg per tree) over three years than trees pruned only (92 kg per tree) or given paclobutrazol only (133 kg per tree), and higher yields than the controls (84 kg per tree) ($P < 0.05$). In the second study (Avilán et al., 2008), the orchard was established with 278 trees per ha. In this experiment, the controls had the smallest increase in tree canopy volume (12%) over four years, followed by the trees treated with paclobutrazol only (17%), and with the trees pruned or pruned and given paclobutrazol much more vigorous (increases in tree canopy volume of 54 and 53%). The first two treatments were significantly different from the last two treatments ($P < 0.05$). Yields were highest in the controls (37 kg per tree), followed by paclobutrazol alone

Table 9
Effect of pruning and paclobutrazol on shoot growth and yield in mango trees growing in India. The trees were pruned after harvest in July, and paclobutrazol applied in September around the base of the tree at a rate of 0.75 g per m of tree canopy diameter. Shoot growth was measured in March. Data are the means of three cultivars collected over a single year. Adapted from Srilatha et al. (2015).

Treatment	Increase in tree height (m)	Increase in tree canopy spread (m)	Yield (kg per tree)
Control	0.31	0.47	15.4
Paclobutrazol	0.17	0.27	24.2
Pruning of current season's growth	0.27	0.38	7.8
Pruning of current season's growth + paclobutrazol	0.12	0.24	22.0
Pruning of previous season's growth	0.37	0.39	5.9
Pruning of previous season's growth + paclobutrazol	0.23	0.28	16.0

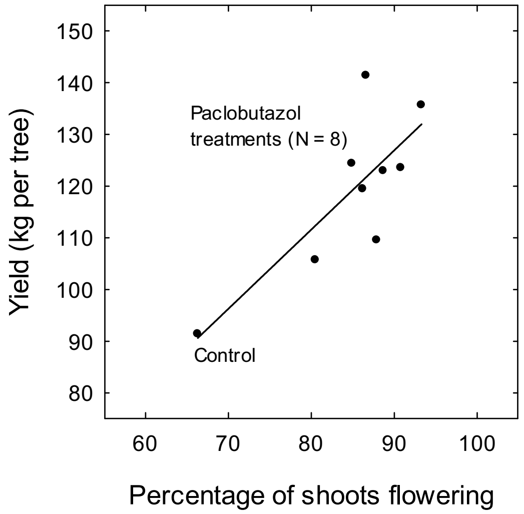

Fig. 23. Relationship between yield and flowering in 'Totapuri' mango trees given paclobutrazol in India. Paclobutrazol (2.5 or 5.0 g per tree) was applied in July, August, September or October (N = 8). Control plots were not treated (N = 1). There was an intermediate relationship between yield and the incidence of flowering ($R^2 = 0.57$). Data are adapted from Reddy et al. (2014).

(33 kg per tree), and pruning + paclobutrazol (24 kg per tree) and pruning alone (23 kg per tree). In the third study (Srilatha et al., 2015), the trees were planted out at 216 trees per ha. In this experiment, pruning had little effect on shoot growth compared with the control trees (Table 9). In contrast, the yields of the pruned trees (without paclobutrazol) were only 40–50% of that of the controls. Paclobutrazol decreased shoot growth when it was applied alone or combined with pruning. The best yields occurred with paclobutrazol alone, and with paclobutrazol and pruning of the current season's growth. Yields in these two treatments were 40–60% higher than the yields of the controls. There was a strong negative relationship between productivity and shoot growth, with yield decreasing with the increase in tree height over the experimental period ($R^2 = 0.67$).

The results of these studies show that paclobutrazol restored productivity when the current or previous season's growth was removed (Kulkarni and Hamilton, 1997; Srilatha et al., 2015) but not when the trees were topped to a height of 2.5 m above the ground (Avilán et al., 2008). This research highlights the difficulty in managing high-density plantings when the trees are pruned severely.

Paclobutrazol persists in soils due to its interaction with organic matter and iron oxides (Milfont et al., 2007, 2008). It is mobile in some soils and can be leached below the root-zone (Costa et al., 2008; Milfont et al., 2008). Residues persist in the soil after frequent or heavy applications of the chemical (Subhadrabandhu et al., 1999; Sharma and Awasthi, 2005a; Sharma et al., 2008; Bhattacherjee and Singh, 2015). High concentrations of paclobutrazol in the top-soil indicate potential contamination of water bodies due to surface run-off (Sharma and Awasthi, 2005b; Shalini and Sharma, 2006; Wu et al., 2012). Residues can also occur in the fruit, although they are usually below the minimum residue limit (MRL) of 0.05 mg per kg (Singh and Ram, 2000; Osuna-García et al., 2001; Costa et al., 2012).

Higher-density orchards require regular pruning to control growth and reduce overcrowding. However, pruning usually stimulates further vegetative growth so the effect on controlling tree size is short lived (Charnvichit et al., 1991; Kulkarni, 1991). There have been numerous studies on the effect of paclobutrazol on the performance of mango orchards. However, only a few studies relate directly to the performance of trees growing at high density. Horticulturists have examined the effect of the growth regulator on shoot extension, the size of the canopy, flowering, fruit set and yield.

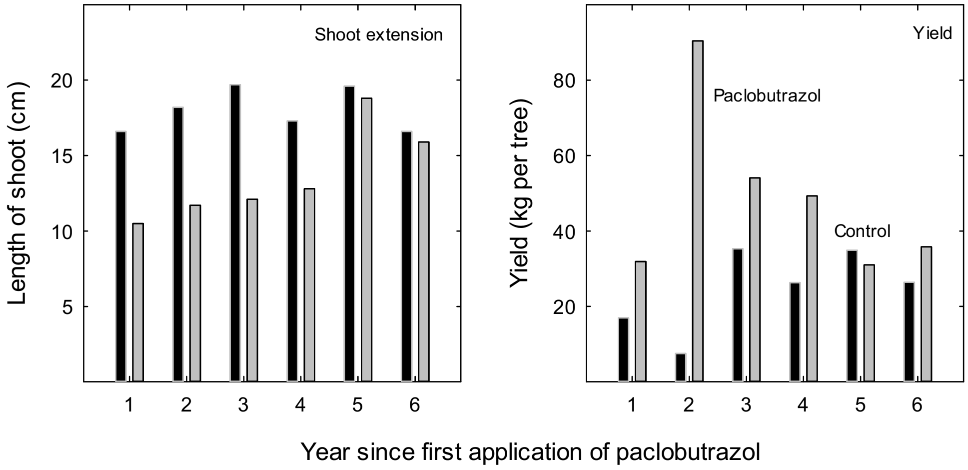

Fig. 24. Effect of paclobutrazol on the performance of 'Alphonso' mango trees grown in India. The growth regulator was applied for the first three years of the experiment, and growth and yield measured for six years. Data are adapted from Reddy and Kurian (2008).

Other researchers have investigated the movement and persistence of the chemical in trees and soils.

Paclobutrazol limits shoot extension in mango trees, with soil applications being more effective than foliar applications or trunk injections. There are insufficient data to indicate whether applications at particular times during the phenological cycle are more effective than at other times. Paclobutrazol usually increases fruit production, and this is often associated with a decrease in shoot growth and an increase in flowering. However in some cases, the increases in yield are mainly due a reduction in tree growth. It is not apparent if paclobutrazol can be used in the long-term management of trees growing at high density. Tree grown at high density normally require some form of canopy management to maintain productivity. However, pruning often leads to excessive vegetative regrowth for one or two seasons. Whether paclobutrazol can be used to counteract this excessive growth in the long term is unknown.

Charnvichit et al. (1991) investigated the effect of the chemical on six-year-old trees in a high-density orchard (1600 trees per ha) in Thailand. The trees were heavily pruned at the start of the experiment to reduce the height of the trees from 2.5 m to 1.7 m, and the spread of the trees from 2.7 m to 1.0 m. The trees produced four flushes over the following season. The height of the trees was reduced by 19% in the plots treated with paclobutrazol compared with that observed in control plots, while the spread of the trees was reduced by 16%. However, the effect of the growth regulator only lasted a year, with the trees soon resuming normal rates of shoot extension. No information on yield was provided by the authors.

Paclobutrazol is mobile in mango trees and soils. There is strong evidence that the chemical persists in the soil for up to a year after being applied. There can be carry-over effects on production for one or two seasons after the last application of the growth regulator (Singh and Bhattacherjee, 2005). This means that producers have to be careful with the dose and to take into account the size of the tree, soil type, rainfall, and the history of the orchard. Excessive applications of the chemical are phytotoxic.

There are concerns about potential contamination of ground and surface water by paclobutrazol, with implications for drinking water supplies (Jonsson et al., 2002; European Food Safety Authority, 2010; Wu et al., 2012). The maximum concentration permissible in drinking water is 0.1 μg per L. Paclobutrazol is not readily degradable in waterways, and has an estimated half-life of 193 days to more than 1000 days. The long-term use of paclobutrazol in mango orchards may be problematic because of concerns with residues in the marketed fruit and contamination of waterways. Kishore et al. (2015) reviewed the use of paclobutrazol in perennial crops, and concluded that there were potential issues for human health through the contamination of ground and surface waters. The risk for contamination was greater in areas where crops were grown on steep slope, when high doses of the chemical were applied with frequent irrigation, and in areas with heavy rainfall.

8. Dwarfing rootstocks and interstocks used to control tree size

Rootstocks have strong effects on the performance of commercial mango orchards (García-Pérez et al., 1993; Smith et al., 1997; Chandan et al., 2006; Crane et al., 2009; Iyer and Schnell, 2009; Ram and Litz, 2009; Bally, 2011). Rootstocks affect the growth of the trees, total productivity and the efficiency of production. They can affect the timing of flowering and harvesting and the quality of the fruit in the market place (Casierra-Postada and Guzmán, 2009). Some rootstocks are able to buffer the trees against saline and calcareous soils and poor quality irrigation waters (Kadman et al., 1976; Gazit and Kadman, 1980; Pandey et al., 2014). There are others that are resistant to diseases such as mango wilt caused by the fungus *Ceratocystis fimbriata* (Rossetto et al., 1997; Arriel et al., 2016). In studies conducted in northern Australia with rootstocks from 95 poly-embryonic cultivars there was no clear relationship between dwarfing in the field and the vigour of the trees in the nursery (Bithell et al., 2016). These data highlight the difficulty in assessing the potential of rootstocks for dwarfing.

The preference of rootstock for mango production varies from country to country. In India, mono-embryonic seedlings of 'Dashehari' are commonly used (Reddy and Raj, 2015). Poly-embryonic seedlings of 'Turpentine' are used in Florida, and poly-embryonic seedlings of 'Kensington Pride' are used in Australia (Smith et al., 2008). The industry in Israel uses 'Saber', '13-1' or '4-9' (Ram and Litz, 2009). Poly-embryonic seedlings are used throughout South-east Asia. The poly-embryonic rootstocks, 'Gomera-1' and 'Gomera-3' from the Canary Islands are widely used in Spain (Durán and Franco, 2006). Several other *Mangifera* species have been suggested as potential rootstocks for commercial production in Florida and South-east Asia (Campbell, 2004; Bompard, 2009). In experiments conducted in Florida, *M. casturi*, *M. griffithii*, *M. laurina*, *M. odorata*, *M. pentandra* and *M. zeyanica* were successfully grafted onto a commercial mango rootstock. It was not stated if the reciprocal grafts were successful (Campbell, 2004). In West Kalimantan, *M. laurina* is occasionally used as a rootstock for common mango trees growing in wet soils (Bompard, 2009). It was considered that better compatibility can be found with species closely related to the commercial mango.

Plant Breeders have attempted to develop better rootstocks for commercial producers. Efforts to develop new germplasm commenced in Israel in the 1950s. This work led to the release of rootstock '13-1' that was suitable for production on calcareous soils or under irrigation with saline water (Gazit and Kadman, 1980). Rootstocks with dwarfing characteristics are less important in this environment with the climate generally not favouring excessive tree growth. A rootstock evaluation program was launched in 1992 in South Africa (Human, 1997; Human et al., 1996; Swanepoel et al., 1998). Although several rootstocks were found to provide higher yields than the 'Sabre' rootstock, the industry standard, none were given commercial consideration (Swanepoel et al., 1998) and 'Sabre' remains the industry favourite. The rootstock breeding program is still continuing in South Africa at the Institute for Tropical and Subtropical Crops at Nelspruit (Sippel et al., 2012).

Interest in developing better rootstocks for mango cultivation in India commenced more than 50 years ago. There have been numerous attempts to select rootstocks that can control tree growth and reduce the variability of production (Reddy and Raj, 2015). There are several areas in India where soil salinity limits mango production. Studies have shown considerable variation in the performance of different rootstocks in this environment. Dinesh et al. (2015b) mentioned the two rootstocks 'Color' and 'Bappakkai' that can withstand high salinity levels. The effect of rootstocks on the performance of mango trees has also been studied in Australia, Thailand, Mexico, Venezuela and Brazil. The focus of many of these studies has been on the potential of dwarfing material. Several studies in India have demonstrated the dwarfing effect of 'Vellaikulumban' on scions of 'Alphonso' and 'Dashehari', however, this rootstock is not used commercially anywhere in India (Reddy and Raj, 2015). These results highlight the difficulty in commercializing potential dwarfing rootstocks.

We provide an overview of the research conducted to assess the impact of rootstocks on the performance of mango orchards. Information is provided on some of the work conducted in Israel, India and Australia. We explored the relationship between yield and tree growth from the various studies (Table 10; Figs. 25–29),

Table 10

Growth and yield of mango trees on different rootstocks in various experiments in Israel, India, Mexico, Brazil, Venezuela, Spain, South Africa and Australia. TH = tree height, Trunk diam. = trunk diameter, Trunk CSA = trunk cross-sectional area, TCD = tree canopy diameter, TSA = tree silhouette area, TCA = tree canopy surface area, and TCV = tree canopy volume. Data adapted from the various reports. The relationship between yield and growth in some of the experiments is shown in Figs. 25–29.

Reference	Country	No. of scions	No. of rootstocks	Record of tree growth	Record of yield	Relationship between yield & tree growth	Rootstocks resulting in small- to medium-sized trees with medium to high yields
Oppenheimer (1958, 1968)	Israel	3–22	5	TH	8 years	Yield increased with growth across all scions/rootstocks.	None
Teotia et al. (1970)	India	1	5	TCD	4 years	Yield increased with growth across all rootstocks.	None
Jauhari et al. (1972)	India	1	5	TH	1 year	Yield increased with growth across all rootstocks.	None
Swamy et al. (1972)	India	2	5–6	TCV	25 years	Yield increased with growth for most combinations of scions/rootstocks.	Neelum/seedling & Neelum/Pahutan
Gowder et al. (1973)	India	1	3	TCV	8 years	Yield tended to increase with growth across all rootstocks.	None
Singh and Singh (1976)	India	1	5	TSA	8 years	Yield increased with growth across all rootstocks.	None
Srivastava et al. (1988b)	India	1	24	TCV		TCV after 7 years ranged from 13–32 m^3 (mean 24 ± 1 m^3).	None
Samaddar and Chakrabarti (1988)	India	2	5	TCV	8 years	No clear relationship between yield & growth across all scions/rootstocks.	None
Kulkarni (1991)	India	2	4	TCV	1 year	No clear relationship between yield & growth across all scions/rootstocks.	None
Reddy et al. (2003)	India	1	8	TCV	17 years	Yield tended to increase with growth across all rootstocks.	None
Singh and Kanpure (2006)	India	1	7	TCV	1 year	Yield increased with growth across all rootstocks.	None
Gawankar et al. (2010)	India	3	2	TCV	4 years	No clear relationship between yield & growth across all scions/rootstocks.	Ratna/Mixed rootstock & Kesar/Vellaikolamban
Singh et al. (2014b)	India	None	8	TCV	8 years	Yield increased with growth in 6 of the rootstock trees.	Vellaikolamban & Chandrakaran
Dayal et al. (2016)	India	5	3	TCV	2 years	No clear relationship between yield & growth across all scions/rootstocks.	Amrapali/Kurakkan
Avila-Reséndiz et al. (1993)	Mexico	1	4 (×4 interstocks)	TCV	5 years	No clear relationship between yield & growth across all interstocks/rootstocks.	None
Ramos et al. (2001, 2004)	Brazil	4	7–8	TH	1–7 years	No clear relationship between yield & growth across all rootstocks (2001 study). Yield increased with growth across some rootstocks, with the other rootstocks producing large trees with small yields (2004 study).	None
Simão et al. (1997)	Brazil	5	7	TCA	3 years	Small variation in growth & yield across all scions/rootstocks.	None
Avilán et al. (1997)	Venezuela	4	9	TCV	2.5 years	No clear relationship between yield & growth across all scions/rootstocks.	None
Durán et al. (2005, 2006) & Durán and Franco (2006)	Spain	1–2	2–4	TCV	2–3 years	Yield increased with growth across all rootstocks.	None
Hermoso et al. (2015)	Spain	1	4	Trunk CSA	4 years	Yield tended to increase with growth across all rootstocks.	None
Swanepoel et al. (1998)	South Africa	4	5		4 years	No data on tree growth.	Not indicated
Human et al. (2000)	South Africa	18–26	2		3–5 years	No data on tree growth.	Not indicated
Santos et al. (2006)	Brazil	3	4	Trunk diam.		Small variation in tree growth across all rootstocks over 2.5 years. No data on yield.	None
Human et al. (2009)	South Africa	2	10		1 year	No data on tree growth.	Not indicated
Smith et al. (2003)	Australia	1	8	TSA	10 years	No clear relationship between yield & growth across all rootstocks.	None
Smith et al. (2008)	Australia	1	64	TSA	4 years	No clear relationship between yield & growth across all rootstocks.	A few rootstocks, including MYP & Brodie

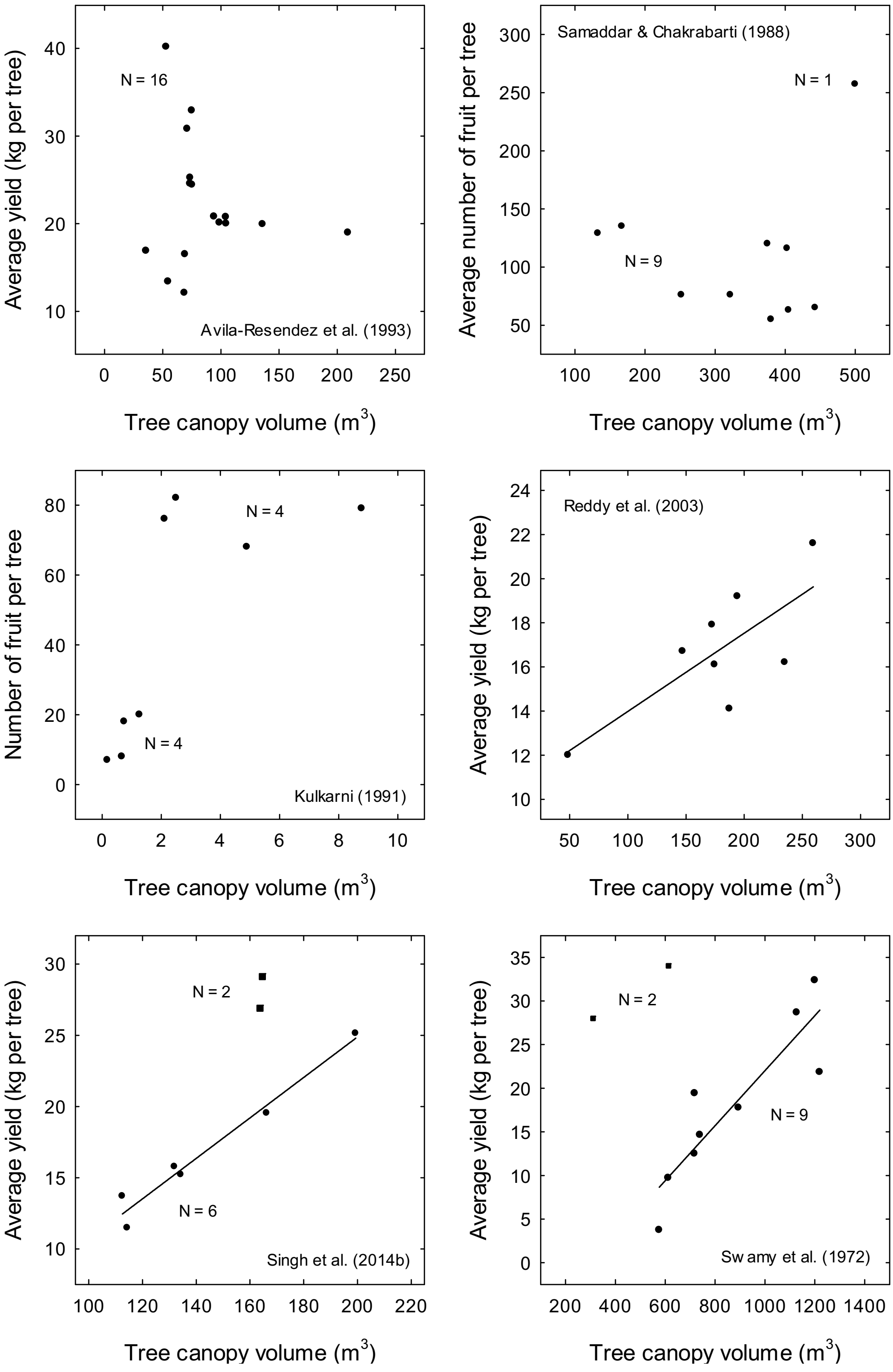

Fig. 25. Relationships between yield and tree canopy volume in mango trees grown with different rootstocks in India and Mexico. Lines show significant regressions. Data are adapted from Swamy et al. (1972), Samaddar and Chakrabarti (1988), Kulkarni, (1991), Avila-Reséndiz et al. (1993), Reddy et al. (2003), and Singh et al. (2014b).

with the idea that dwarfing rootstocks would typically result in small- to medium-sized trees with medium to heavy yields.

Some of the earliest work on the role of rootstocks in mango cultivation was conducted by Oppenheimer (1958, 1968) in Israel. He reported on two experiments conducted at the Volcani Institute in Bet Dagan. In the first experiment, the rootstock 'Sabre' was found to be superior in terms of total fruit production compared with that obtained with 'Warburg' or '14.12'. Yield was related to the size of the trees, with trees grafted onto 'Sabre' generally larger and more uniform than the trees grafted onto the other two rootstocks. In the second experiment, 'Sabre' was found to be superior, '3.2' somewhat inferior, and '14.12' inferior. Two other rootstocks were similar to 'Sabre', although further data were required to confirm their commercial potential. 'Sabre' was later evaluated in South Africa and northern Australia and gave good yields or mixed yields (Smith et al., 2003, 2008; Human et al., 2009). These results highlight that the effect of rootstocks on the performance of mango orchards can vary in different growing areas.

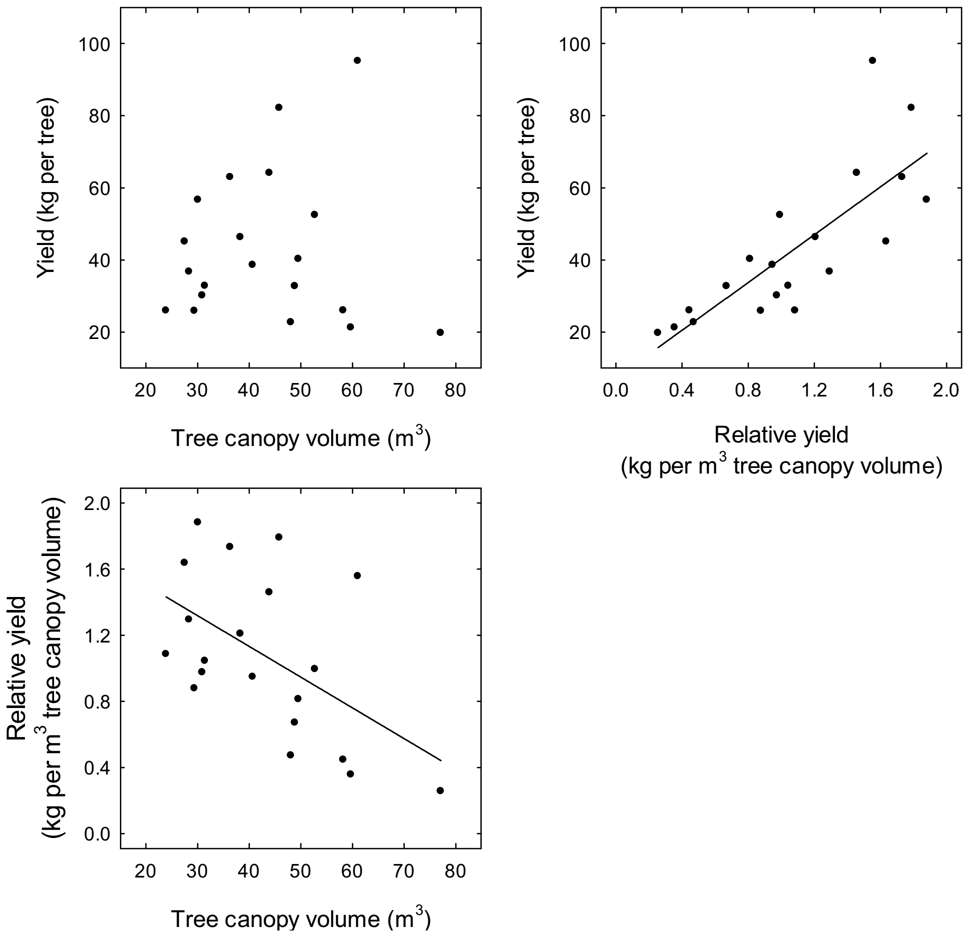

Fig. 26. Relationships between yield, relative yield and tree canopy volume in 'Edward', 'Haden', 'Springfels' and 'Tommy Atkins' mango trees grown with four different rootstocks in Venezuela. Lines show significant regressions. Data are adapted from Avilán et al. (1997).

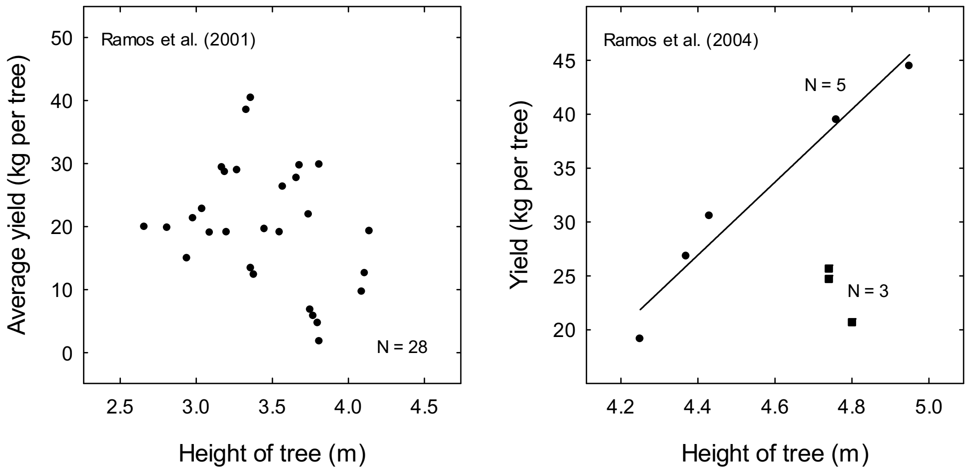

Fig. 27. Relationships between yield and tree height in mango trees grown with different rootstocks in Brazil. Line shows significant regression. Data are adapted from Ramos et al. (2001, 2004).

Information collected by Reddy et al. (2003) and Singh et al. (2014b) indicated that cultivars/rootstocks affected the productivity of mango orchards in India. In the first experiment, average yields of 'Alphonso' grafted onto eight different rootstocks over 17 cycles of production ranged from 12.0 kg per tree (rootstock 'Vellaikulamban') to 21.6 kg per tree (rootstock 'Muvandan'). Tree canopy volume at the end of the experiment ranged from 49 to 259 m^3 with the same two rootstocks. In the second experiment, average yields of eight cultivars grown on their own root systems ranged from 11.5 kg per tree (rootstock 'Olour') to 29.1 kg per tree (rootstock 'Vellaikolamban'). In this experiment, two out of the eight fruiting cycles were off-years with no crops. Information collected by Reddy et al. (2003) indicated that there was a moderate relationship between yield and tree canopy volume ($R^2 = 0.50$), although the data were highly variable (Fig. 25). Calculated efficiency of fruit production ranged from 0.07 to 0.11 kg per m^3 with

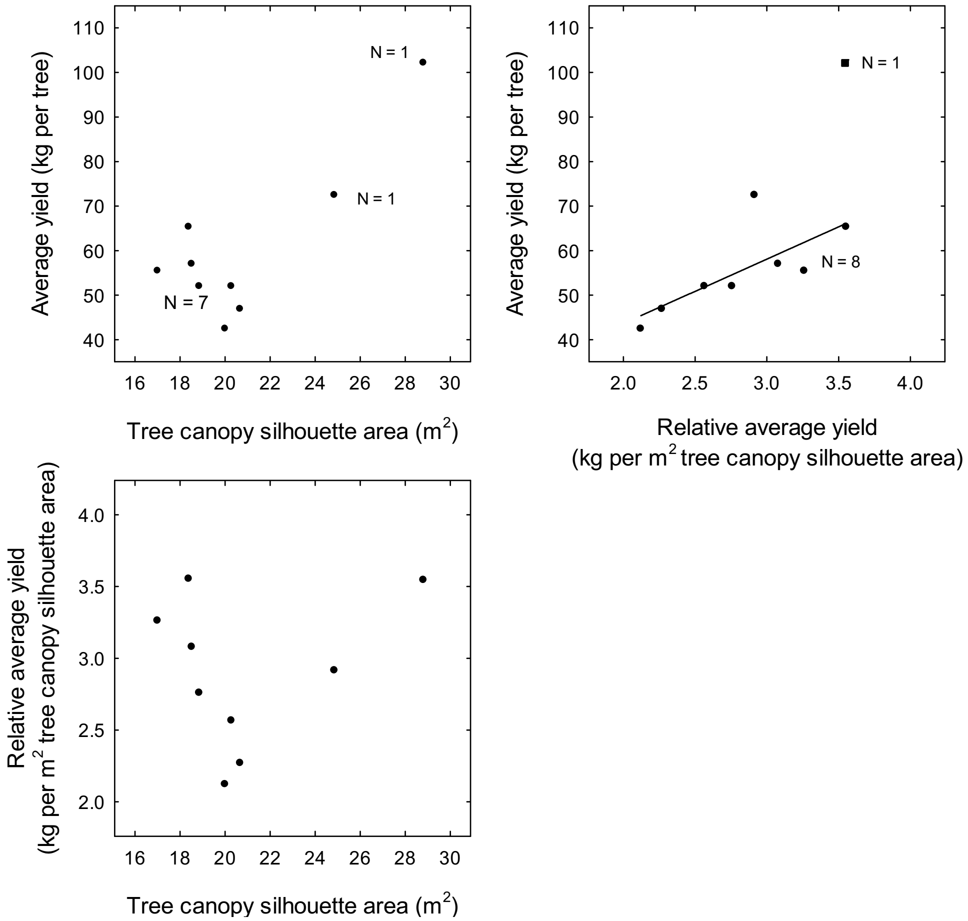

Fig. 28. Relationships between yield, relative yield and tree canopy silhouette area in 'Kensington Pride' mango trees grown with nine different rootstocks in Australia. Line shows significant regression. Data are adapted from Smith et al. (2003).

seven of the rootstocks, and was 0.25 kg per m^3 for 'Vellaikulamban'. In Australia, 'Vellaikulamban' produced a small tree but only moderate yields (Smith et al., 2008).

The data collected by Singh et al. (2014b) indicated that there was a strong relationship between yield and the size of the canopy in six out of the nine rootstocks ($R^2 = 0.96$), and a separate group including 'Vellaikolamban' and 'Chandrakaran' with intermediate canopies and high yields (Fig. 25). These two cultivars had higher relative yields (0.16 or 0.18 kg per m^3 tree canopy volume) than the other cultivars (0.10–0.13 kg per m^3 tree canopy volume).

Avilán et al. (1997) studied the productivity of mango trees grafted onto nine rootstocks and grown at a density of 278 trees per ha in Venezuela. Tree canopy volume ranged from 22 to 77 m^2 per tree, with an average (±SE) across the cultivars and rootstocks of 43 ± 3 m^3 per tree. Yield ranged from 20 to 95 kg per tree, with an average across the cultivars and rootstocks of 43 ± 5 kg per tree. There was no relationship between absolute yield and the size of the trees (Fig. 26). In contrast, absolute yield was related to the efficiency of production per unit of tree canopy volume ($R^2 = 0.60$).

Ramos et al. (2001, 2004) determined the relationship between productivity and tree growth with different rootstocks in Brazil. In the first experiment, there were only small differences in the growth of the trees across the different rootstocks (average heights of 3.3–3.6 m pooled across the four scions in 1996), whereas the yields under the different rootstocks varied by about a factor of two (16–29 kg per tree). There was no relationship between yield and the height of the trees (Fig. 27). In the second experiment, the height of the trees ranged from 4.3 to 5.0 m under the different rootstocks, while yields ranged from 19.1 to 44.5 kg per tree. Yield increased with tree height ($R^2 = 0.95$) in one group of trees, while in the other group the trees had relatively large canopies and small yields (Fig. 27).

Smith et al. (2003, 2008) examined the effect of rootstocks on the productivity of 'Kensington Pride' trees growing in the Northern Territory in Australia. In the first experiment, the scion was grafted onto nine rootstocks, while in the second experiment the scion was grafted onto sixty-four rootstocks. Growth was assessed by calculating the canopy silhouette area by taking photographs from each side of the trees (Chapman et al., 1986; Richards, 1992).

In the first study, canopy silhouette area in year ten ranged from 17 to 29 m^2 per tree, with an mean (± SE) across the rootstocks of 21 ± 1 m^2 per tree (Smith et al., 2003). Average yield ranged from 42 to 102 kg per tree, with a mean across the rootstocks of 61 ± 6 kg per tree. In the second study, canopy silhouette area in year six ranged from 4 to 8 m^2 per tree, with an mean across the rootstocks of 6 ± 0.1 m^2 per tree (Smith et al., 2008). Average yield ranged from 9 to 48 kg per tree, with a mean across the rootstocks of 24 ± 1 kg per tree.

In the two experiments in Australia, there was no clear relationship between productivity and tree growth (Figs. 28 and 29) (Smith et al., 2003, 2008). In the first experiment, there was one group of trees with small canopies and low yields, and two rootstocks providing large canopies and intermediate ('False Julie') or high yields ('Sg. Siput') (Smith et al., 2003). The performance of 'Sabre', the well-known rootstock from South Africa was disappointing, and provided the lowest yield of the nine rootstocks evaluated. In the second experiment, 'MYP' from an unknown source was an example of a small tree (canopy silhouette area of 5.1 m^2) with good

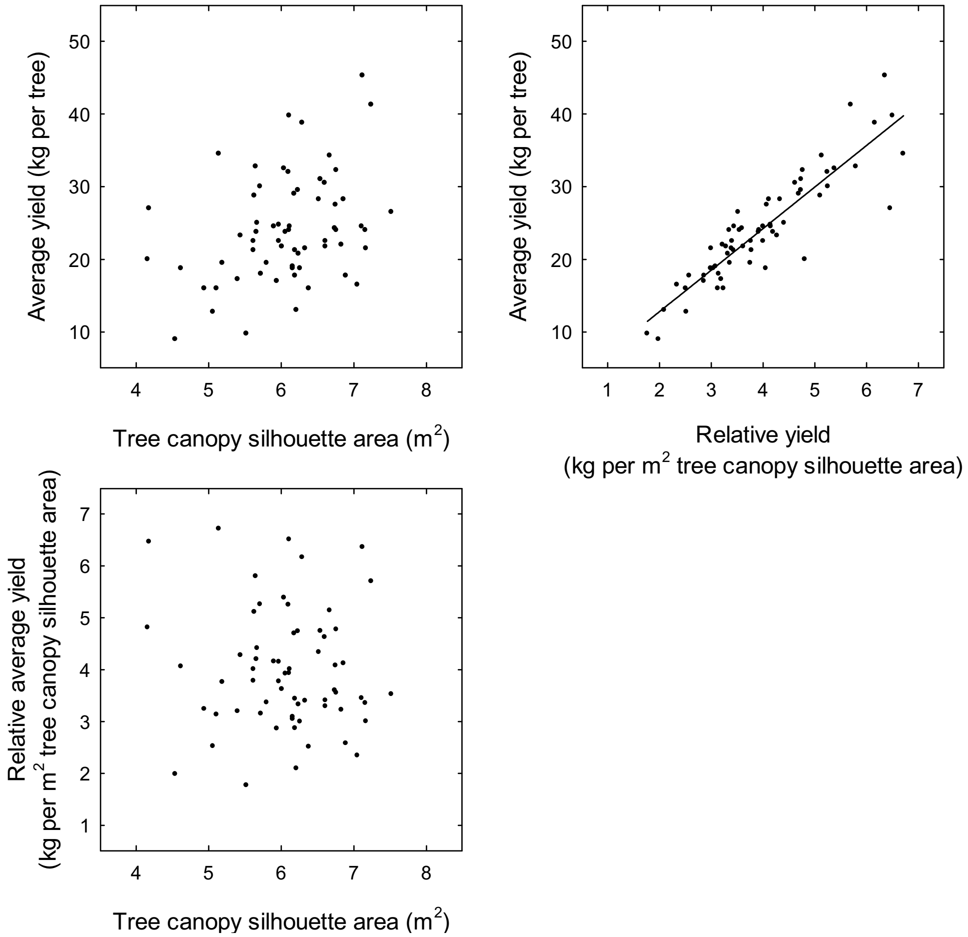

Fig. 29. Relationships between yield, relative yield and tree canopy silhouette area in 'Kensington Pride' mango trees grown with 64 different rootstocks in Australia. Line shows significant regression. Data are adapted from Smith et al. (2008).

production (average yield of 35 kg per tree) (Smith et al., 2008). 'Brodie' from Australia was also small (canopy silhouette area of 4.2 m^2) with good production (average yield of 27 kg per tree). 'B' from Indonesia and Malaysia was an example of a large tree (canopy silhouette area of 7.1 m^2) with good production (average yield of 45 kg per tree). 'Sabre' was relatively productive, while 'Sg. Siput' was mediocre. There was a strong relationship between absolute yield and relative yield based on the size of the canopies in eight out of the nine rootstocks in the first study (Fig. 28; Smith et al., 2003) and in all 64 rootstocks in the second study (Fig. 29; Smith et al., 2008). The exception to this pattern was 'Sg. Siput' in the first study, which had higher yields than expected probably due to its large canopy.

Rootstocks have a strong effect on the growth and productivity of mango trees (Table 10). We were interested in determining whether some of the rootstocks have a dwarfing effect. Potential commercial rootstocks include those cultivars that restrict the growth of the scion, without significantly reducing productivity. These rootstocks are typically associated with high relative yields or high yield efficiencies. We assessed the relationship between yield and growth in the various rootstock experiments. There were typically three types of responses in these data sets (Figs. 25–29). In the first type, there was no clear relationship between fruit production and tree size (Avilán et al., 1997 in Fig. 26; Ramos et al., 2001 in Fig. 27; and Smith et al., 2008 in Fig. 29). In other words, there were some small trees with at least intermediate yields. The second type of response was variable. Some were small trees with low yield, small trees with high yields, large trees with small yields and large trees with large yields (Avila-Reséndiz et al., 1993, Samaddar and Chakrabarti, 1988; and Kulkarni, 1991 in Fig. 25; and Smith et al., 2003 in Fig. 28). The small trees with high yields had high yield efficiencies or relative yields and would be considered to be dwarfing (Table 10). In the third type of response, yield increased as the size of the trees increased for at least some of the rootstocks (Reddy et al., 2003, Singh et al., 2014b, and Swamy et al., 1972 in Fig. 25; and Ramos et al., 2004 in Fig. 27). In other words, yield efficiency was similar in the different rootstocks, and there was no evidence of potential commercial dwarfing.

It has been proposed that interstocks can be used to control the growth of mango trees, with several studies conducted in India, Japan, Mexico, Venezuela and Brazil. Various indices of tree growth have been recorded, including tree height, the diameter, circumference or area of the trunk, canopy silhouette area, canopy surface area and canopy volume. Overall, the effect of interstocks on tree growth and yield was small (Table 11). In some instances the effect of rootstock on the performance of the trees was greater than the effect of the interstocks (Srivastava et al., 1988a).

There has been considerable research examining the effect of rootstocks on the performance of mango orchards. Some researchers have studied the growth of different cultivars as potential rootstocks, while others have grafted named cultivars onto different rootstocks. Most of the studies ran for up to ten years, although there are a few that ran for longer. Yield was determined by counting or weighing the fruit on each tree. Various methods were used to estimate tree growth, including tree height, tree canopy silhouette area, tree canopy surface area and tree canopy

Table 11
Growth and yield of mango trees on different interstocks in various experiments in India, Japan, Mexico, Puerto Rico, Brazil, and Venezuela. Data adapted from the various reports.

Reference	Country	No. of scions & rootstocks	No. of interstocks	Record of tree growth	Record of yield	Response to interstock
Srivastava et al. (1988a)	India	1 (2 rootstocks)	12	Tree height, trunk girth & tree canopy diameter	None	Rootstock had a greater effect on tree growth than interstock.
Avila-Reséndiz et al. (1993)	Mexico	1 (3 rootstocks)	3	Shoot dry weight & leaf area expansion	None	Growth was least on Irwin interstock/Irwin rootstock, & on Esmeralda interstock/Manila rootstock.
Zarrameda et al. (2000)	Venezuela	3 (6 rootstocks)	4	Tree canopy volume	None	Small effect of interstock on growth which ranged from 3.2–3.7 m^3 in Haden, 1.4–2.7 m^3 in Tommy Atkins, and 1.8–2.3 m^3 in Edward.
Veloso et al. (2004)	Brazil	3 (1 rootstock)	1	Tree height, trunk girth, tree canopy diameter, & tree canopy volume	None	Mean tree canopy volume of 34 m^3 with interstocks and 33 m^3 without interstocks.
Yonemoto et al. (2007)	Japan	3 (1 rootstock)	2	Trunk circumference	None	Small variation in girth of the scion (11.5–16.8 cm).
Perez et al. (1988)	Puerto Rico	2 (1 rootstock)	5	Tree height & trunk diameter	6 years	Small differences in tree height across different interstocks. Irwin interstock best for yield in Palmer, but no response in Edward.
Avila-Reséndiz et al. (1993)	Mexico	4 (5 rootstocks)	5	Tree height, trunk cross-sectional area, tree canopy diameter, & tree silhouette area	5 years	Yields ranged from 60–201 kg per tree in the various combinations of scion/interstock/rootstock.
Sampaio and Simão (1996)	Brazil	1 (1 rootstock)	3	Tree height & tree canopy diameter	6 years	Interstock did not affect tree growth or yield.
Vazquez-Valdivia et al. (2000)	Mexico	1 (1 rootstock)	1	Tree canopy volume	5 years	Trees grafted onto interstocks had smaller canopies (16.4–21.7 m^3) than trees grafted directly onto rootstocks (24.4 m^3). Interstocks had no effect on yield (33–46 kg per tree).

volume. Data on tree growth and fruit production have been used to calculate relative yield or yield efficiency per unit of tree growth. In many of these studies, there was a strong relationship between yield and the size of the trees. In other words, the highest yields occurred in the largest trees. There were only a few instances where rootstocks resulted in small- to medium-sized trees with medium to large yields. These rootstocks would be potential dwarfing material, but there is little evidence of their commercialization.

Dwarfing rootstocks have the obvious advantages in producing small to medium canopies and medium to high yields but are not widely used in modern mango orchards (Table 10). Iyer and Kurian (1992) suggested that the growth of the mango trees can be better managed with chemicals such as paclobutrazol than with rootstocks. The other possibility is to use dwarfing cultivars or scions rather than dwarfing rootstocks.

9. Dwarfing scions to reduce tree size

India is considered to be the world's richest germplasm centre for mango, with more than 1000 recognized cultivars. Allopolyploidy or polyploidy due to crossing of different species, out-breeding and a wide range in growing environments has promoted considerable diversity in the crop (Ravishankar et al., 2013). Most of the cultivars are the result of open pollination, with significant variation in the performance of seedlings and named cultivars (Lavi et al., 2004; Joshi et al., 2013a). The architecture and form of the tree varies with the cultivar and growing conditions, and changes as the trees age (Ram, 1993; Mem et al., 2016). Tree canopy volume and yield can vary significantly across different cultivars (Prasad et al., 2016).

In an extensive study of 115 cultivars in West Bengal, the trees were classified as dwarf, dwarf to medium, medium to tall, or tall (Mitra et al., 2013). The branches were classified as erect, sub-erect or spreading. The canopies were described as round, oval-shaped, dome-shaped or in between. Within the population assessed, nine cultivars were classified as dwarf (including 'Amrapali' and 'Mallika'), four cultivars as dwarf to medium, seven cultivars as medium to tall, and twenty-one cultivars were classified as tall. In another study in India with 33 different cultivars (17-year-old trees), yields ranged from 12 to 154 kg per tree, with a mean (±SE) of 59 ± 4 kg per tree (Rai et al., 2001). The height of the trees ranged from 4.7 to 8.5 m, with a mean of 6.5 ± 0.3 m, and tree canopy volume ranged from 38 to 153 m^3, with a mean of 89 ± 13 m^3. There was a high estimate of heritability for yield (96%), and a lower estimate of heritability for tree canopy volume (54%). There was no clear relationship between yield and the size of the trees in this study.

Joshi et al. (2013a) grew nine cultivars in India and collected data on vegetative growth when the trees were 20-years-old. Tree canopy volume ranged from 17 to 497 m^3, with a mean of 278 ± 58 m^3. Most of the cultivars, including 'Bombay Green', 'Chausa', 'Langra' and 'Mallika' were classified as vigorous, while 'Dashehari' and 'Amrapali' were classed as less vigorous. 'Amrapali' produced the smallest canopy in this experiment. 'Mallika' has been reported to be dwarfing in other studies in India (Mitra et al., 2013).

Iyer et al. (1988) examined the relationship between yield and tree growth in 42 cultivars. The trees were seven-years-old and were growing in Karnataka. The trees produced two to five growth flushes over the year of the experiment, and had 5–247 fruit at harvest. There was a weak positive relationship between yield and the height of the trees ($r = 0.34$). In this study, the sizes of the trees and fruit yield were highly heritable across the population, with a general heritability of more than 70% for both characters.

Although there is a large genetic diversity of mango in India, only about 40 cultivars are widely grown (Rai et al., 2001; Naidu and Naidu, 2009; Campbell and Ledesma, 2013; Das, 2013). Some cultivars such as 'Mallika' and 'Amrapali' were released more than 25 years ago (Sharma et al., 1980). The importance of the different cultivars varies across the different growing areas of the country. In many of the other mango-growing areas of the world, commercial production is usually based on a few cultivars (Bally et al., 2009b; Fivaz, 2009; Knight et al., 2009; Calatrava et al., 2013; Campbell and Ledesma, 2015; Schneider et al., 2015). 'Tommy Atkins' accounts for about 80% of production in Brazil, with smaller plantings of 'Palmer' (Pinto et al., 2004).

Efforts to develop better cultivars have been made in several countries, including India, Israel, South Africa, Florida and Brazil (Carstens et al., 1996; Human, 1997; Human et al., 2000, 2013; Swanepoel et al., 1998; Pinto et al., 2004; Bally et al., 2009a,b; Campbell and Zill, 2009; Gunjate, 2009; Iyer and Schnell, 2009; Sippel et al., 2012; Campbell and Ledesma, 2013; Human et al., 2013). Only a few cultivars have been developed using deliberate open-pollination or cross-pollination. Most of the commercial material has been selected from chance seedlings or clones, usually on the basis of the quality of their fruit (Mukherjee et al., 1968; Lavi et al., 1993, 1997; Usman et al., 2001; Pinto et al., 2015). Plant improvement in the crop is difficult because of the long juvenile period of the trees before they begin to fruit, the large variation in the performance of established clones, and the large area required to grow and assess potential commercial material. The fruit set only one seed which are sometimes difficult to germinate. Heavy fruit drop can reduce the harvest of fruit after pollination (Pérez et al., 2016). Many of the main cultivars are also poly-embryonic reducing the genetic diversity of the offspring.

An early analysis of more than 1000 hybrids in India suggested that dwarfing, regular bearing and precocity were controlled by recessive genes (Sharma and Majumder, 1988). In this study, only two useful cultivars were produced out of about 1000 hybrids developed from cross-pollination ('Mallika' from 'Neelum' × 'Dashehari', and 'Amrapali' from 'Dashehari' × 'Neelum'). Of these two cultivars, only the latter combined dwarfing, regular bearing and good fruit quality. Overall, dwarfing cultivars are not widely exploited in commercial mango growing. Studies conducted in Brazil showed that dwarfed male parents did not always produce seedlings with small canopies (Pinto and Byrne, 1993). Dwarfing can also lead to small fruit, compact inflorescences and increase the susceptibility of the tree and the fruit to attack by insects (Bally et al., 2009a).

An analysis of the performance of different cultivars shows that the relationship between fruit production and growth varies in different experiments (Table 12). In first type of response, there was at least a weak positive relationship between yield and tree growth across some of the cultivars with *P* values generally < 0.02 (Singh and Singh, 1988; Kurian and Iyer, 1997; Rathor et al., 2009; Reddy et al., 2011; Bakshi et al., 2012; Singh et al., 2013; Fig. 30) (Prasad et al., 2016; Fig. 31). These results indicate that overall yield efficiency was similar in the different cultivars. In a few of these experiments, there were some cultivars that did not follow the general response. For example, in the work of Kurian and Iyer (1997), there was a group of four cultivars ('Langra', 'Gola', 'Maharaja Pasand', and 'Kalepad' or 'Kerala') that produced medium to large trees and low to high yields. The data collected by Singh et al. (2013) indicate that 'Bangalore' typically produced a small tree with a high yield and was considered dwarfing.

In the second type of response, there was no clear relationship between yield and growth (Kobra et al., 2012; Lu et al., 2013; Kaur et al., 2014; Silva et al., 2014; Gill et al., 2015; Fig. 31). In these experiments, some cultivars produced small to medium canopies and medium to high yields. Examples of these cultivars include 'Irwin' (Lu et al., 2013), 'Dashehari', 'Rattual', 'Local Selection No.1' (Kaur et al., 2014), and 'Tommy Atkins' (Silva et al., 2014). There

Table 12

Growth and yield of mango cultivars in various experiments in India, Bangladesh, Brazil and Australia. TH = tree height, TSA = tree silhouette area, TCA = tree canopy surface area, and TCV = tree canopy volume. Data adapted from the various reports. The relationship between yield and growth in some of the experiments is shown in Figs. 30 and 31.

Reference	Country	No. of cultivars	Age of trees	Record of tree growth	Record of yield	Range in tree growth	Range in yield	Relationship between yield & tree growth	Dwarfing cultivars with medium to high yields
Singh and Maurya (1986)	India	12	12-years-old	TSA	4 years	23–110 m^2	59–213 kg per tree	Yield increased with growth in 11 cultivars.	None
Shrivastava et al. (1987)	India	15	1-year-old	TCV	7 years	2–7 m^3	2–7 kg per tree	No clear relationship between yield & growth.	Bangalora & Neelum
Singh and Singh (1988)	India	13	No information	TSA	7 years	30–112 m^2	20–230 kg per tree	Yield increased with growth in 11 cultivars.	None
Kurian and Iyer (1997)	India	24	9-years-old	TCV	2 years	2–104 m^3	3–33 kg per tree	Yield increased with growth in 20 cultivars.	None
Chanana et al. (2005)	India	5	No information	TCV	1 year	57–311 m^3	16–73 kg per tree	Yield increased with growth in all cultivars.	None
Shivanandam et al. (2007)	India	15	5-years-old	TCV	2 years	6–16 m^3	7–24 kg per tree	No clear relationship between yield & growth.	Arka Neelkiran & Mallika
Rathor et al. (2009)	India	20	22-years-old	TCV	3 years	13–179 m^3	4–45 kg per tree	Yield increased with growth in all cultivars.	None
Reddy et al. (2011)	India	19	6-years-old	TCV	7 years	6–113 m^3	1–19 kg per tree	Yield increased with growth in all cultivars.	None
Bakshi et al. (2012)	India	8	13-years-old	TCV	1 year	29–390 m^3	110–254 fruit per tree	Yield increased with growth in all cultivars.	None
Kobra et al. (2012)	Bangladesh	12	13-years-old	TCV	1 year	22–80 m^3	18–84 kg per tree	No clear relationship between yield & growth.	None
Joshi et al. (2013b)	India	9	20-years-old	TCV	1 year	13–420 m^3	30–185 kg per tree	No clear relationship between yield & growth.	Dashehari
Lu et al. (2013)	Australia	5	4-years-old	TCA	2 years	45–108 m^2	25–62 kg per tree	No clear relationship between yield & growth.	Irwin
Singh et al. (2013)	India	18	28-years-old	TCV	8 years	108–709 m^3	7–116 kg per tree	Yield increased with growth in 17 cvs.	Bangalora
Kaur et al. (2014)	India	14	No information	TCV	1 year	66–2156 m^3	44–149 kg per tree	No clear relationship between yield & growth.	Local Selection, Dashehari & Rattaul
Silva et al. (2014)	Brazil	5	2-years-old	TH	2 years	2.5–3.9 m	3–19 kg per tree	No clear relationship between yield & growth.	Tommy Atkins
Gill et al. (2015)	India	10	35-years-old	TCV	1 year	106–647 m^3	39–226 kg per tree	No clear relationship between yield & growth.	None
Kumar et al. (2015)	India	16	23-years-old	TCV	5 years	26–153 m^3	4–35 kg per tree	No clear relationship between yield & growth.	Dashehari
Prasad et al. (2016)	India	8	8-years-old	TCV	3 years	9–117 m^3	5–18 kg per tree	Yield increased with growth in all cultivars.	None

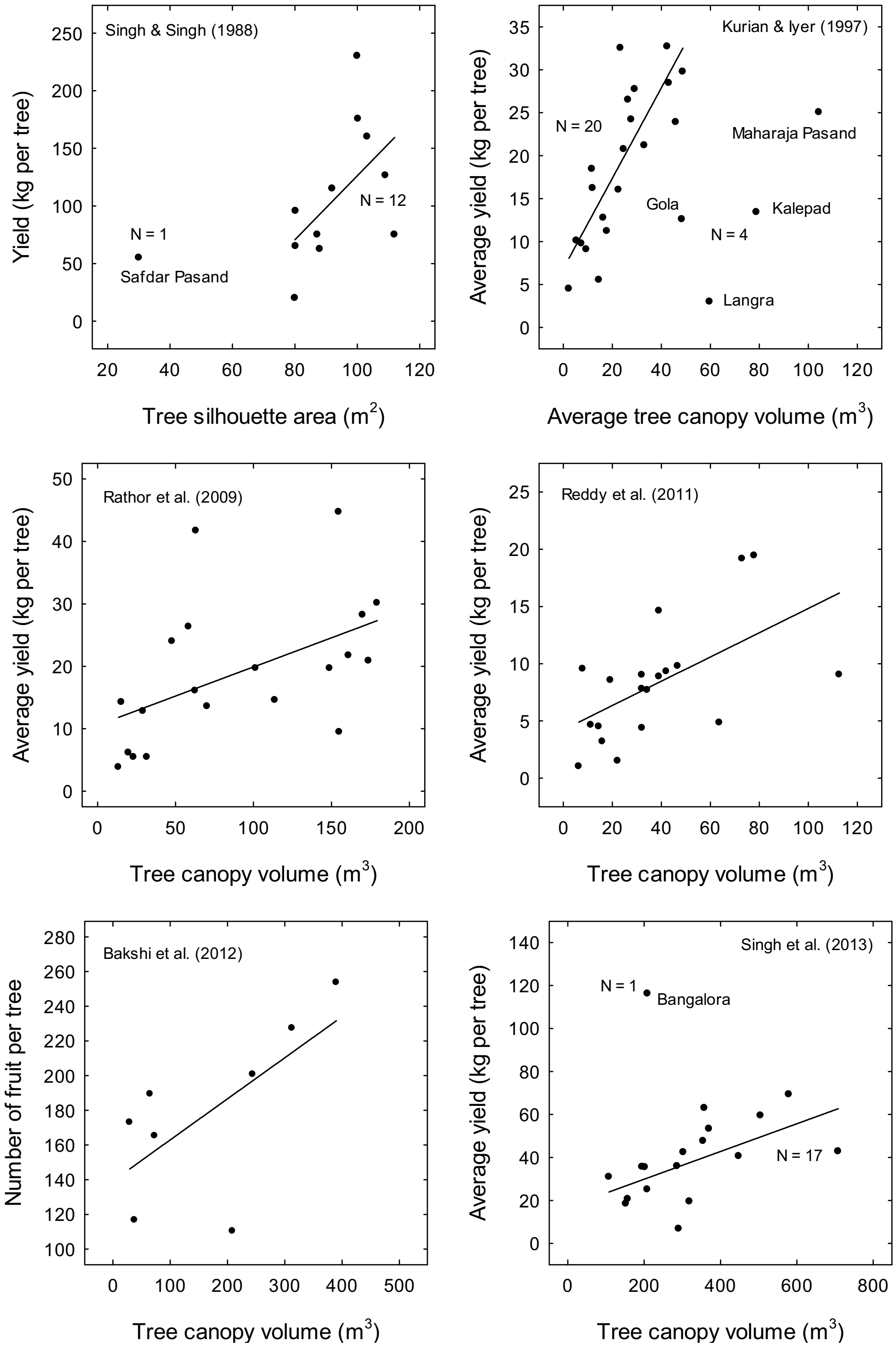

Fig. 30. Relationships between yield and tree silhouette area or tree canopy volume in mango cultivars grown in India. Lines show significant regressions. Data are adapted from Singh and Singh (1988), Kurian and Iyer (1997), Rathor et al. (2009), Reddy et al. (2011), Bakshi et al. (2012), and Singh et al. (2013).

was a large variation in relative yields in the different experiments, which tended to decrease as the size of the trees increased (data not presented).

Overall, the results of the analysis suggest that the size of the tree is more important in determining fruit production than the relative efficiency of fruit production. Large trees had higher yields despite being less efficient in fruit production on a canopy basis. There were a few exceptional cultivars that produced small trees with heavy production in both relative and absolute terms. This means that canopy volume is not sufficient to infer yield potential. Architectural studies can be used to assess the relationship between productivity and tree growth (Lauri et al., 2009; Normand et al., 2009; Dambreville et al., 2013; Rosati et al., 2013; Connor et al., 2014).

There has been considerable effort to improve the performance of mango cultivars around the world. There are thousands of named cultivars, although commercial production in most growing areas is based on just a few. The majority of the commercial cultivars have been selected from chance seedlings, with the use of open- or cross-pollination to produce new cultivars being relatively recent.

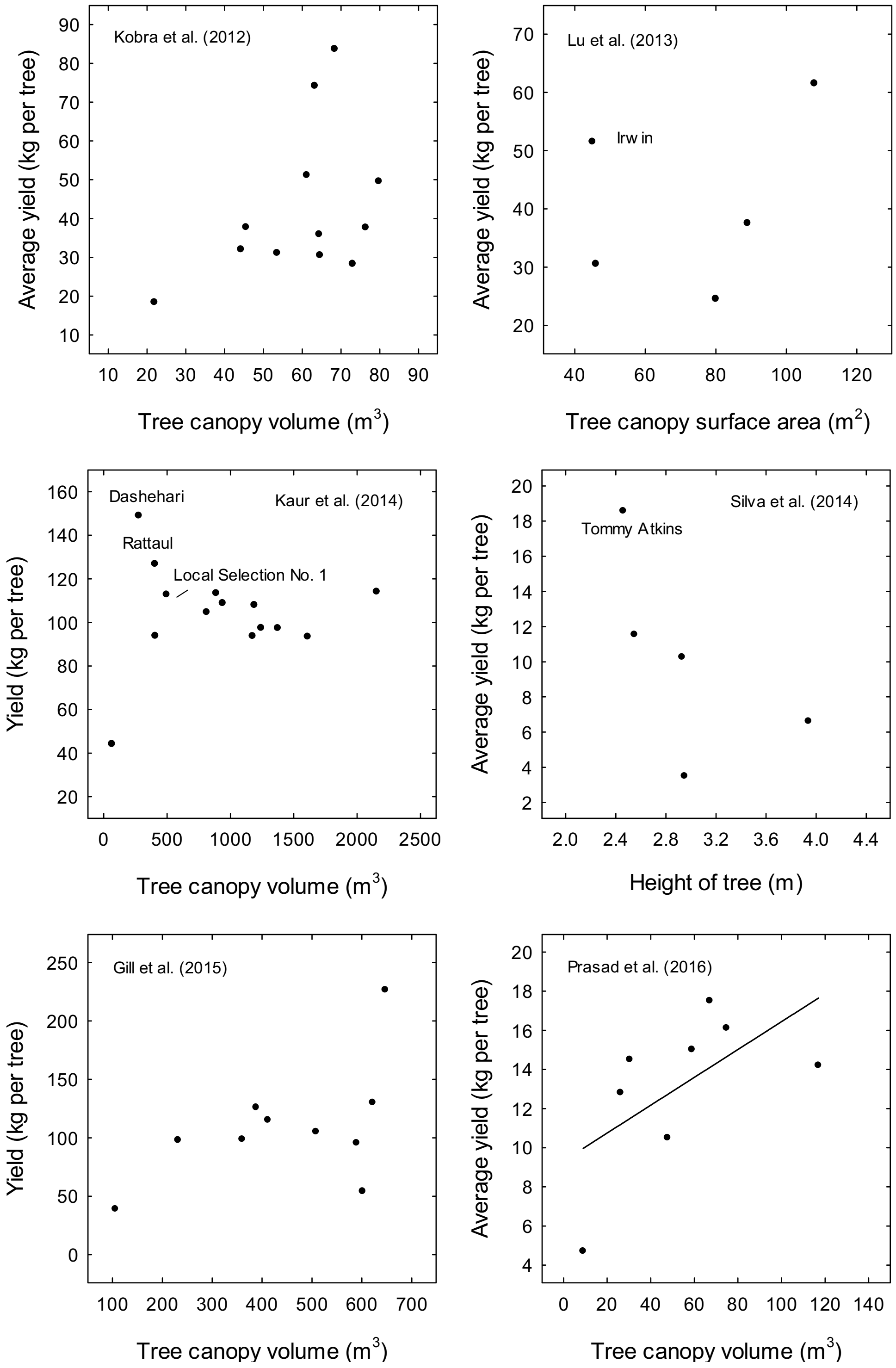

Fig. 31. Relationships between yield and tree height, tree canopy surface area or tree canopy volume in mango cultivars grown in India, Bangladesh, Brazil and Australia. Line shows significant regression. Data are adapted from Kobra et al. (2012), Lu et al. (2013), Kaur et al. (2014), Silva et al. (2014), Gill et al. (2015), and Prasad et al. (2016).

Many of the new cultivars produced over the past twenty years are not widely grown, and some industries are still based on cultivars selected decades ago.

The main focus of plant improvement has been to develop cultivars with excellent eating quality and marketing appeal. There has been less effort made to develop small trees that produce heavy crops. Dwarfing cultivars have been developed in India, Brazil and elsewhere, however, these cultivars are generally not widely utilized. Analysis of the relationship between yield and the size of the trees indicates that there are variations in yield efficiency across different cultivars; however, yields tend to increase with the size of the canopy. Only a few of these experiments have been conducted over several seasons. Cultivars which are classified as dwarfing in one study may not always be dwarfing in other studies. Further research is required to identify cultivars that consistently produce small trees with heavy yields.

10. Implications of the previous research on the viability of high-density plantings

Mango trees are grown in many regions around the world from the warm tropics to the cool subtropics. Under ideal growing conditions, the trees can grow into large specimens, and this makes spraying and harvesting difficult. Trees growing in traditional orchards are planted at about 100–200 trees per ha. Yield per tree generally increases over time until the trees start to crowd and shade each other, and then yield declines. Productivity on a per-hectare basis is quite low in the early years of the orchard, and it takes some time to pay for the initial costs of the trees and establishing the orchard.

There has been significant interest in growing mango orchards at high density. However, most orchards are still grown at relatively low densities of 100–200 trees per ha. There are very few commercial orchards planted at higher densities up to 600 trees per ha. The main problem with medium- to high-density plantings is that over-crowding begins earlier than in traditional orchards. Once the trees start to shade each other, production usually falls. Attempts to control the growth of the trees with pruning have not always been successful and often result in the loss of production for one or more seasons. Research has been conducted to assess whether the growth of the trees can be controlled through dwarfing cultivars and rootstocks, better canopy management and the application of growth regulators. There are only a few examples where these strategies have provided good productivity over the long term. Research needs to integrate the main factors affecting the productivity of high-density orchards. These include potential dwarfing cultivars and rootstocks, and canopy management systems.

There is no consensus on the ideal planting density for commercial mango orchards, with the optimum ranging from 200–4000 trees per ha in various studies. This is possibly related to the large variation in experimental approaches adopted by different researchers. Most of the experiments have been conducted for only a few years after planting, with few examples of experiments extending over more than ten years. Future research should examine the response of the trees up to about 800 trees per ha. Higher planting densities are not likely to recover the establishment costs and the initial growing expenses.

There is a major issue with several of the studies on planting density in mango, with details of the rootstocks used or the type of pruning carried out not indicated in the reports. Information needs to be collected on the economics of different production systems in mango, taking into account the additional planting and maintenance costs associated with high-density plantings. A review of the viability of planting systems in olive in Spain showed that high-density orchards planted at 250–700 trees per ha were more profitable than super-high-density orchards planted at over 1500 trees per ha (Freixa et al., 2011). Low to medium vigour olive cultivars are generally more suited to high-density plantings than high vigour cultivars (Farinelli and Tombesi, 2015; Proietti et al., 2015). Low vigour cultivars typically have shorter and narrower hedgerows and a high leaf to wood ratio.

Mango has a long history of cultivation in India and throughout the rest of Asia. Production has also spread to most of the tropical and subtropical world with significant industries in Africa and the Americas. Thousands of cultivars have been selected over the last few hundred years, with deliberate open- or cross-pollination carried out more recently. Most of the effort in plant breeding has been to produce and identify cultivars with good eating and marketing characteristics. There have been fewer attempts to develop dwarfing cultivars with heavy production. There is a large variation in the architecture and size of the trees in different growing areas, with some dwarfing cultivars developed in India and elsewhere. Many of the cultivars that have been developed are not widely planted, and not exploited in high-density plantings. There are few studies that have examined the productivity of different cultivars in high-density orchards. Research in olive indicated that some cultivars are more suited to intensive production than other cultivars (Trentacoste et al., 2015b; Vivaldi et al., 2015). Some cultivars also responded better to pruning. Similar research needs to be conducted in mango.

There have been several attempts to develop dwarfing mango rootstocks. It was thought that these rootstocks would contribute to the development of high-density plantings in the absence of small-growing scions. Unfortunately few, if any, dwarfing rootstocks have been commercialised. The effect of the rootstocks has not always been consistent across different growing areas. In some cases, the use of dwarfing rootstocks has resulted in lower yields compared with the use of standard rootstocks. At other times the trees on the dwarfing rootstocks still needed regular canopy management or regular applications of growth regulators to control growth. Numerous rootstocks have been released over the past 20 years, but few are widely grown. In most situations the highest yields are achieved with large trees. Further efforts need to be made to explore the relationship between productivity and the size of the canopy with different rootstocks. It is not known whether the use of dwarfing rootstocks will reduce the need for intensive canopy management in high-density orchards.

Efforts have been made to control the size of mango trees through effective canopy management. In some orchards, trees have been grown as individual specimens, while in other orchards the trees have been grown as hedgerows that are pruned regularly. Attempts have also been made to prune the trees to particular shapes to improve light interception and distribution. Effective canopy management is essential if high-density plantings are to be exploited. Many researchers have recorded lower yields in pruned trees compared with unpruned trees. The best responses have been achieved with annual light pruning. Yields are more consistent with this approach compared with the response achieve with less frequent but more severe pruning. The timing of pruning also needs to take into account the impact of shoot growth on the success of flowering (Wilkie et al., 2008). There is some indication that pruning part of tree to improve the distribution of light to the lower section of the canopy can improve overall productivity.

Further experiments are required to develop effective canopy management strategies in mango orchards. There is a significant body of research in apple and olive that may have application to pruning, light interception and yield in mango canopies (Connor et al., 2009; Gómez-del-Campo et al., 2009; Lauri et al., 2009; Larbi et al., 2015; Trentacoste et al., 2015a,b,c). Information needs to be collected on the relationship between productivity, leaf area and light interception in different parts of the mango tree canopy. A good starting point would be to explore these ideas in a range of dwarfing and non-dwarfing cultivars. This work should include information on the effect of tree architecture on productivity (Lavee et al., 2012). There is work in other tree crops, where remote sensing has been used to estimate the various parameters used to calculate tree canopy volume, include the height of the tree and the diameter of the tree canopy (Díaz-Varela et al., 2015; Torres-Sánchez et al., 2015).

The response of mango trees to growth regulators, particularly the response to paclobutrazol has been well studied. There have been many examples where paclobutrazol has reduced vegetative growth and increased fruit production. However, in some cases, the results have been mixed. The growth regulator reduced vegetative growth but had no effect on fruit production. Some of the research has involved application of the growth regulator over just one or two seasons. There have been few studies that have examined the

Table 13
Proposed approaches to study the key issues affecting the productivity of high-density mango orchards.

Key issue	Recommendation
Orchard layout	Develop the orchard as hedgerows rather than as individual trees.
Planting density	Compare plots planted at 400 or 660 trees per ha. Control plots would be planted at 200 trees per ha.
Cultivar	Use 1 or 2 cultivars that have consistently produced small to medium trees with medium to heavy crops.
Rootstock	Use 1 or 2 rootstocks that have consistently produced small to medium trees with medium to heavy crops.
Canopy management	Hedge the tops and the sides of the trees along the rows to remove 0.2–0.3 m of the canopy soon after harvest.
Experimental design	Plots of each planting density/cultivar need to be planted in blocks.
Replication	Use at least six trees in each plot, and at least six blocks (replicates)
Length of experiment	The experiment would need to be run for at least 20 years.
Profitability	Conduct an economic analysis of the different planting and growing strategies.
Relationship between productivity and light levels	Evaluate various canopy management strategies, including the thinning of internal branches. Determine whether the lower sections of the canopy contribute to overall productivity. This would be a separate experiment to the main plant density experiment.

effect of pruning and paclobutrazol on the yields of high-density plantings over several years.

Paclobutrazol can persist in mango trees and soils, giving rise to concerns regarding residues of the chemical in marketed fruit in some countries. There are also concerns about contamination of surface waters in areas with heavy rainfall and in orchards grown on steep slopes. The introduction of new plant growth regulators to replace paclobutrazol appears relatively unlikely in the near future (Rademacher, 2015). This is because new chemicals are expensive to develop and few chemical companies are interested in developing compounds for a relatively niche market.

Further research is required to develop high-density orchards in mango. The main factors influencing the productivity of the trees, include cultivar, rootstock and canopy management. These factors need to be integrated for success. The development of high-density orchards is not likely in near future until we have a better understanding of how these factors affect the relationship between productivity, leaf area and light interception in different parts of the canopy.

11. Suggested research

There are a few key issues to consider before conducting research to study the productivity of high-density orchards (Table 13).

The first issue is whether the trees should be grown as individual trees or in hedgerows? The second issue is what range in planting density to use? The third issue is what cultivar and rootstock to use? Finally a decision has to be made about the type of canopy management to be employed to control the growth of the trees.

Individual mango trees have potentially higher yields on a per tree basis than hedgerows. This is because individual trees can produce fruit over the whole canopy, at least until adjacent trees start to crowd each other. In contrast, hedgerows produce fruit only on the top of the hedge and on the edges of the hedge along the inter-rows. Most high-density plantings of tree crops have been developed as hedgerows, mainly because of practical issues, including the ease of pruning, spraying and harvesting. Individual trees must be pruned more severely than hedges and this adds to the costs of canopy management.

None of the previous research has indicated an optimum planting density for mango, in terms of long-term sustainable yields per ha. The experience in other crops suggests that very close plantings are not likely to be economically viable once the extra costs of the trees, establishment and tree agronomy are taken into account. High-density orchards require intensive canopy management and unless well-tested strategies are available, severe pruning is likely to reduce production. A good approach might be to compare plots planted at 400 trees per ha (5 m between adjacent rows and 5 m between adjacent trees along the rows) and plots planted at 660 trees per ha (5 m between adjacent rows and 3 m between adjacent trees along the rows). Control plots would be planted out at 200 trees per ha (10 m between adjacent rows and 5 m between adjacent trees along the rows).

Plots of each planting density need to be planted in blocks, using an appropriate experimental design. Each plot should have at least six trees, and there probably needs to be at least six replicates (blocks). This design would allow a valid comparison of the performance of the two planting systems. The experiment would need to be conducted over at least 20 years. Most mango trees do not begin to produce commercial crops until about five years after planting. Yields per tree usually increase up until about year ten, and then start to decline as the trees shade each other. Most of the previous studies on high-density orchards ran for about ten years, and were terminated just as the trees along the rows were starting to grow into each other. An economic analysis needs to be completed to determine the viability of the different planting and growing systems (Elkins et al., 2008). This would be to determine whether the higher planting and growing costs of the high-density orchards are more than compensated by the higher returns.

Dwarfing cultivars and rootstocks have been developed for mango orchards, although few of these genotypes have been used commercially. This may be because the response of the material has not been consistent across different growing areas. An initial approach would be to include one or two dwarfing cultivars/rootstocks that have consistently shown to produce small to medium trees and medium to large crops.

The long-term viability of a high-density orchard is dependent on successful canopy management. The best approach is probably to hedge the tops and sides of the canopy along the rows after harvest, removing no more than 0.2–0.3 m of the canopy. More severe pruning is likely to remove too much of the canopy or is likely to encourage excessive regrowth (Pastor et al., 2007). Canopy management could include removal of some of the internal branches and shaping of the trees to improve the distribution of light to the lower sections of the canopy. Separate experiments need to be conducted to determine the contribution of the lower canopy to the productivity of the tree. Various pruning/thinning treatments could be applied to hedgerows, and the relationship between yield and light levels determined.

12. Conclusions

Mango has been cultivated in India for thousands of years, with this popular fruit also cultivated in many other countries over the last few hundred years. There has been strong interest in planting orchards at more than 100–200 trees per ha to take advantage of early production in the trees and to quickly recover the costs of establishing the plantings. The trees naturally grow into large specimens up to 10 m high or more and this makes spraying and harvesting difficult in traditional orchards. The development of orchards planted up to 4000 trees per ha is dependent on strategies to control tree growth and improve light interception and distribution as the trees begin to crowd and shade each other.

Numerous cultivars and rootstocks have been developed over the past few hundred years, but few of these have been planted at high density. Effective canopy management strategies have yet to be developed that can be readily integrated into high-density growing systems. Pruning at the wrong time, at the wrong severity or at the wrong interval can inhibit flowering and cropping for one or more seasons. Growth regulators such as paclobutrazol have been used to control tree growth, but there are only a few examples where they have been integrated in the management of high-density plantings. The long-term future of this chemical is uncertain because of concerns about residues in some markets and contamination of ground waters. Optimum planting densities for mango trees vary from 200 to 4000 in different experiments, and there are only a few examples of successful integration of existing technologies to control tree growth. The development of high-density plantings is dependent on the use of dwarfing cultivars and/or rootstocks and better canopy management systems than currently employed. This research may take some time to deliver viable high-density plantings.

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