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Dynamics of long-term adaptive responses in growth and rubber yield among *Hevea brasiliensis* genotypes introduced to a dry sub-humid climate of Eastern India

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ABSTRACT

The twentieth century has witnessed a transformation of Para rubber (*Hevea brasiliensis*) from a wild tree species to a major plantation crop of South and Southeast Asia. In India, rubber cultivation was started in Southern India because of agro-climatic suitability, but pressure on land resources has necessitated further expansion to neighbouring areas. Earlier attempts to afforest isolated pockets of Central and Eastern India have met with limited success due to various factors. This paper reports a long-term evaluation (sixteen years) of niche adaptation of twelve rubber clones introduced to Eastern India. The growth and survival pattern indicated good adaptability for certain clones such as RRII 430 that recorded the highest girth and tappability. Early yield pattern identified RRII 429, RRII 430, and RRII 422 as higher yielders having 20–30% yield advantage over the control clone RRIM 600. The clones PB 217, RRIM 600, RRIC 100, and RRII 203 showed better stability and moderate yield rankings. There was individual clonal dominance for yield components such as dry rubber content (RRIC 100, RRII 417), bark thickness (RRII 203), and number of latex vessel rows (RRII 430, RRII 417). This is the first report on the performance of the latest Indian rubber clones of the RRII 400 series from the region. The clonal adaptability in this region that can be translated into commercial benefits included rising trend in latex yield and desirable secondary traits. Due to the uncertainty of stress occurrence in the non-traditional regions, planting of genetically variable clones (multiclones) in commercial plantings is important to impart adaptive plasticity. The results assume prominence in the context of expansive rubber cultivation and improving productivity in non-traditional areas and for international multilateral clone exchange aimed at improving global rubber productivity.

1. Introduction

Para rubber (*Hevea brasiliensis* Muell. Arg.), a tree native to Amazonian river basins of South America was a wild species until the late nineteenth century. This was one of the most recently domesticated species of the world to exploit natural rubber from its latex. The milky white latex of Para rubber tree contains more than 30% of *cis*-1, 4-polyisoprene, a natural polymer popularly known as natural rubber. Natural rubber is a vital industrial raw material used for making thousands of indispensable products used by us. Established at the commercial plantation level, global supplies of natural rubber are met mainly from Southeast Asian countries. Thailand, Indonesia, and Vietnam are the major global producers, whereas China, India, and USA are the major consumers of natural rubber (Rubber Board, 2017). As a tropical rainforest tree, Para rubber is adapted naturally to the equatorial climate, and therefore is grown widely under well-distributed rainfall and a temperature range of 25–34 °C (Vijayakumar et al., 2000).

Niche testing is a practice in crop introduction, which is basically testing a new crop at a particular environment. It is in contrast to multi-location testing and looks for site-specific adaptation (Sperling and Ashby, 2000) rather than homeostasis. Since the demand for natural rubber is increasing globally, production and productivity increase is mandated in all rubber growing countries. International Rubber Research and Development Board (IRRDB) is currently encouraging

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multilateral clone exchange programmes between its member nations, wherein widely adapted high yielding clones are mostly preferred for exchange targeting direct adoption for cultivation.

As a novice crop of the twentieth century with great commercial potential, *H. brasiliensis* is largely cultivated in the equatorial belt between 10°S and 10°N latitude, known as the traditional belt. Several crop adaptation trials precede the clonal recommendations for commercial cultivation in these areas. In India, the traditional belt encompasses southern part of Kerala and Kanyakumari district of Tamil Nadu where optimum climatic requirements for rubber cultivation prevails. Being a perennial tree crop, the spread of commercial plantations in traditional regions soon encountered land limitations, which compelled the researchers and policy makers to look beyond the traditional belt for extensive cultivation (Sethuraj et al., 1989). However, the non-traditional regions had limitations, mostly climatic, in the form of extreme weather conditions such as drought, low temperature, and wind for which rubber trees are highly vulnerable. To leverage cultivation in these regions, therefore, requires intrinsic tolerance against biotic and abiotic stresses and adaptation (Priyadarshan, 2003).

India is agro-climatically diverse, and four regions are recognised as non-traditional areas for rubber cultivation. They are Eastern, Northeast, Konkan, and subtropical high-altitude regions (Vijayakumar et al., 2000). In Eastern India, areas that may be marginally suitable for cultivation comprise of selected localities in the states of Odisha (Baripada in Mayurbhanj District, Balasore, and Dhenkanal districts), Chhattisgarh (Sukma in Bastar District), Andhra Pradesh (Rampachodavaram in East Godavari District), and West Bengal (parts of Jalpaiguri District). Some of these areas suffer from severe drought during summer except Jalpaiguri where winter is cooler. Other regions also have climatic limitations such as severe drought coupled with high temperature, low relative humidity, and high light intensity in the Konkan (Chandrashekar et al., 1998); cold, wind, and hailstorms in the Northeast (Priyadarshan, 2003), and cold, landslides, and acidic soils in the sub-tropical high altitude regions.

Successive exploratory surveys in Eastern India (Rubber Board, 1985) have revealed vast potential of these regions not only for extending rubber cultivation but also for integrated rural/tribal area development (Brahmam, 2002; Brahmam and Thirunavoukkarasu, 2005). Consequently, the Rubber Board of India has established a regional research station at Kadlipal in Dhenkanal district of Odisha to evaluate the adaptive and yielding potential of different rubber clones through niche testing trials as well as to develop suitable agro-technologies for the region. Preliminary reports on the performance of a few older *Hevea* clones (Gupta et al., 2001, 2002; Krishan 2013a,b) indicate that the most popular indigenous hybrid clone of the traditional region, RRII 105 does not perform well in this region. Further, no detailed study of clonal adaptation and pattern of genotype × environment interactions in the region is available as of now. Recent reports indicate that five new hybrid clones, RRII 414, RRII 417, RRII 422, RRII 429, and RRII 430 had out-performed RRII 105 in the traditional areas (Licy et al., 2003; Mydin et al., 2011). They were also reported to excel in the non-traditional areas of Northeast India and Sub-Himalayan West Bengal (Antony et al., 2010; Meenakumari et al., 2011; Das et al., 2015). A large-scale clonal evaluation trial of 12 promising clones including the new clones was planted in Bhubaneswar in the state of Odisha during 1996. The objective of this study was to evaluate the clones for their long-term performance in terms of growth, early yield, and desirable secondary traits as a measure of their site-specific adaptation to the local climate. It was hypothesised that clones combining stable high latex yield and growth would possess stress adaptation under the prevailing agro-climatic conditions in the region.

2. Materials and methods

2.1. Experimental location and weather

The trial was planted in the experimental farm of the CSIR-Institute of Minerals and Materials Technology (CSIR-IMMT), Bhubaneswar (20°15′N, 85°52′E and 45 m MSL). The soil type was Inceptisol (Aeric Tropaquept), characterised by sandy loam texture (83.2% sand, 6.6% silt, and 10.2% clay) with pH of 5.52 and EC of 0.076 $dS\,m^{-1}$ (Mohapatra and Panda, 2010). The soil was sufficiently deep for rubber culture. Long-term (50 years) average weather data at the site shows annual average temperature in the range of 22 °C to 32 °C, with a mean minimum of 15.2 °C during December-January and a mean maximum of 37.2 °C during May. Annual average rainfall of 1554 mm is received between June and September through south-west monsoon in 58 rainy days. The highest average monthly rainfall of 367 mm occurs in August (www.weatherbase.com). The region has no serious threat of persistent winds and other adverse factors such as frost, but seasonal cyclonic disturbances are a regular feature.

2.2. Clonal material

Twelve clones including nine indigenous hybrid clones, a primary clone, and three exotic hybrids were included in the trial (Table 1). Among these, RRIM 600 was widely acclaimed as a clone adapted to non-traditional areas. Developed from the cross between Tjir 1 and PB 86 in Malaysia, RRIM 600 is a clone that was tested and cultivated globally. Its well-known characteristics such as average tolerance to cold and drought, and above average tolerance for wind, qualify itself as an ideal control clone for adaptive comparison. All the clonal materials were maintained in bud-wood (source bush) nurseries, directly cloned from the respective mother trees, before being developed as planting materials for the study.

2.3. Field layout and upkeep

The trial was laid out during 1996 in a randomised complete block design with three replications. Each clonal plot consisted of 25 trees planted at a spacing of 4.9 m × 4.9 m. All the cultural operations and irrigation during the early phase of establishment were given as per the recommended practice for non-traditional areas (Vijayakumar et al., 1998). Three years after planting, on October 29, 1999, a category 5 tropical super cyclonic storm (BOB 03), lashed coastal Odisha with winds gusting to 260 $km\,h^{-1}$ (Thomalla and Schmuck, 2004) and inflicted heavy damage to the young plants. Timely intervention could salvage the trial almost in its entirety by propping up of plants and supply of casualties.

Table 1
Clones included in the study along with parentage.

Clone	Parentage	Origin
PB 217	PB 5-51/PB 6-9	Malaysia
RRIC 100	RRIC 52/PB 83	Sri Lanka
RRII 51	Primary clone	India
RRII 105	Tjir 1/Gl 1	India
RRII 176	Mil 3-2/PB 5-60	India
RRII 203	PB 86/Mil 3-2	India
RRII 414	RRII 105/RRIC 100	India
RRII 417	RRII 105/RRIC 100	India
RRII 422	RRII 105/RRIC 100	India
RRII 429	RRII 105/RRIC 100	India
RRII 430	RRII 105/RRIC 100	India
RRIM 600	Tjir 1/PB 86	Malaysia

PB, Prang Besar; RRIC, Rubber Research Institute of Ceylon; RRII, Rubber Research Institute of India; RRIM, Rubber Research Institute of Malaysia; Tjir, Tjirandji; Gl, Glenshiel; Mil, Milakande.

2.4. Data collection

Data collection was planned at two phases, growth during the immature phase (pre-tap) and growth and yield during the mature phase (post-tap). Girth was recorded annually beginning from the 2nd year after planting (YAP) and continued during the entire study period. The rate of growth was recorded as girth increment (cm $year^{-1}$). Girth recording was carried out with a measuring tape, as circumference of the main trunk, at a height of 150 cm from the bud union. Further, the young trees were tested at 5th YAP for early yielding potential. For this, a miniature incision known as 'test-tap' was made on the young trees and the cumulative dry rubber yield for ten successive tappings (g $tree^{-1}$) was recorded. Tapping is the harvest process for latex collection from the rubber tree, in which a long downward sloping half-spiral incision running from left to right is made on the tree bark. The latex oozing out is collected in plastic cups fixed just below the bottom end of the cut. During 2009, on attaining maturity, the trees were opened for regular tapping by adopting a tapping system of S/2 d3 6d/7 (Vijayakumar et al., 2009). For each clone, the measure of uniformity in attaining the suitable girth for tapping known as 'tappability' was determined as the number of trees that have attained a girth of 50 cm (tap girth) at a height of 125 cm from the bud union among the total number of trees of that clone and expressed as percentage. A minimum required tappability of 50% (threshold tappability) for all the clones was set for the commencement of yield collection. In the present study, all the clones crossed the threshold tappability in the 12th YAP. Yield data were recorded for four years (1st to 4th year of tapping) at fortnightly intervals by cup coagulation method (Nair et al., 2012). The dry weight of the rubber lumps was measured using a portable top pan balance and expressed as grams per tree per tap (gtt) as a measure of yield. Annual measurements were made on tree girth (cm), while seasonal measurements at lean yielding phase (May) and peak yielding phase (November) were done during 3rd and 4th year of tapping for measuring yield component traits, such as volume of latex as ml per tree per tap (mltt) and dry rubber content (DRC) as percentage (w/v). Girth increment rate was computed from the girth data for a block of four years before and after tapping. Tapping rest was given for two months during peak summer for two years. Weather data of the study site was collected from India Meteorological Department, Bhubaneswar.

Besides the growth and yield data, anatomical parameters such as bark thickness (mm), and number of latex vessel rows were recorded in the 6th (immature) and 12th (at first harvest) YAP. Bark samples were collected from four randomly selected trees per plot at a height of 150 cm from the bud union on the opposite side of the tapping panel and preserved as per standard procedure (Johansen, 1940). 100 µm thick radial longitudinal sections (RLS) were cut using a sledge microtome. The sections were stained using Oil Red O (Omman and Reghu, 2003) for visualising the latex vessels and the data was recorded from five image fields per sample under a bright field microscope. The data were subjected to mixed model analysis of variance (ANOVA) wherein the clonal effects were taken as the fixed factor and the year and interaction effects as random. The mean comparison was performed by Duncan's Multiple Range Test (DMRT) to test for significant difference between clones. Data analysis was done using restricted maximum likelihood (REML) method implemented in the statistical analytical suite, CropStat v.7.2 (IRRI, 2009).

2.5. Genotype x environment interactions

Genotype response to environments is key to ecological adaptation, which can help us to assess their adaptive potential. In a perennial tree like *Hevea*, temporal adaptive behaviours are crucial factors that can endure the species for its lifetime. Therefore, we have assessed yield stability of genotypes by estimating the clone × year interactions for the first four years of tapping. Further, an analysis of repeated measures was performed to assess the temporal dynamics of the yielding behaviour of the clones during this period. Genotype-Genotype-Environment (GGE) biplots (Yan, 2001) were generated using GenStat v.12.0 software (Payne et al., 2009) using environment-centered model.

3. Results

3.1. Weather data

The weather data during the study period (Supplementary Fig. 1) showed a mean maximum temperature (T_{max}) of 38 °C during May and a mean minimum (T_{min}) of 16 °C during December–January period. The interval between March and mid-June was the hot period. Mean relative humidity was ~80% during morning hours and ~70% in the evening. Maximum rainfall was observed in July–August (350–400 mm) during the south-west monsoon. Rainfall distribution was highly skewed and the north-east monsoon showers were scanty. Average annual rainfall was 1598 mm. A prolonged post-monsoon phase was observed from November to April with very low (< 50 mm) cumulative rainfall.

3.2. Growth and tappability

Growth curve plotted for the 16 years showed that clonal differences were not prominent in the early years. There was apparent clonal variability observed towards the mature phase (6th YAP). While all the other clones exhibited cross-over interactions between years, RRII 430 was the only clone that performed consistently well over the years by maintaining high growth rate throughout the period. The growth trend before and after tapping did not show a significant difference in most of the clones (Fig. 1).

At the time of commencement of tapping (opening), highest tappability (89%) was observed in the clone RRII 430 (Table 2) followed by RRII 414, RRII 417, and RRII 422 (> 70%). While RRII 429 recorded relatively low tappability (52%), the lowest tappability was observed in RRII 51 and RRII 176. Additionally, there was difference in the time of attainment of the threshold tappability among the clones. RRII 417, RRII 422, and RRII 430 were more precocious than the rest of the clones by one year.

Average girth at opening varied from 49.65 cm (PB 217) to 62.04 cm (RRII 430). RRII 430 maintained the highest mean girth

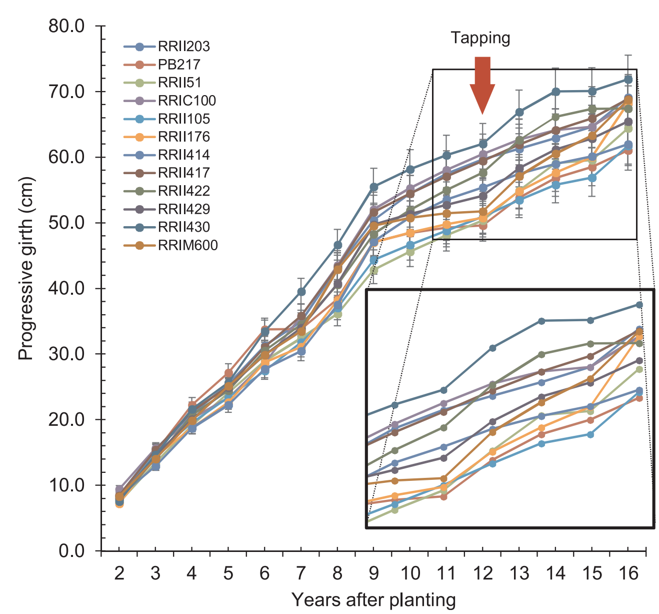

Fig. 1. Growth curve of the experimental clones for sixteen years. The growth pattern of all clones in the initial years remained almost similar. Tapping began at twelfth year after planting.

Table 2
Girth at opening and girth increment rate of clones.

Clone	12th YAP[a]		Girth at 16th YAP (cm)	Age to threshold tappability[b] (YAP)	Girth increment rate	
	Tappability (%)	Girth (cm)			Pre-tap	Post-tap
PB 217	55.0[bcd]	49.7[f]	58.6[cd]	12.0	2.8 (38.1)	2.9 (15.8)
RRIC 100	74.0[b]	60.5[ab]	64.7[abc]	12.0	4.2 (29.3)	1.9 (23.0)
RRII 51	52.0[cd]	50.4[f]	59.6[cd]	12.0	3.6 (39.4)	3.5 (27.9)
RRII 105	55.0[bcd]	51.0[f]	56.9[d]	12.0	3.5 (38.9)	2.7 (12.7)
RRII 176	51.0[d]	50.8[f]	60.0[bcd]	12.0	3.1 (37.6)	4.4 (21.1)
RRII 203	64.0[bcd]	59.1[b]	64.7[abc]	12.0	4.1 (32.8)	2.4 (34.5)
RRII 414	72.0[bc]	55.4[cd]	60.1[bcd]	12.0	4.5 (47.6)	1.7 (11.9)
RRII 417	73.0[b]	59.5[ab]	65.9[abc]	11.0	4.1 (37.4)	2.4 (15.8)
RRII 422	70.0[bcd]	57.7[bc]	67.4[ab]	11.0	4.3 (42.0)	2.5 (17.0)
RRII 429	52.0[cd]	54.1[de]	62.9[abcd]	12.0	3.3 (32.8)	2.8 (20.9)
RRII 430	89.0[a]	62.0[a]	70.1[a]	11.0	3.8 (32.9)	2.5 (15.9)
RRIM 600	59.0[bcd]	51.8[ef]	63.3[abcd]	12.0	2.2 (20.7)	4.3 (32.6)
SE	3.4	1.3	1.1	–	2.0	2.0
CV (%)	18.6	8.1	6.3	–	19.0	36.1

Values followed by a common letter are not significantly different at 95% confidence level by Duncan's multiple range test (DMRT); YAP, years after planting.
[a] The time when the trees were tapped for latex for the first time; girth increment rate was computed for a block of four years before (pre-tap) and after (post-tap) commencement of tapping; values in parenthesis are % increment.
[b] Threshold tappability of 50%.

(70.13 cm) at 16th YAP, followed by RRII 422 (67.40 cm), whereas RRII 105 recorded the lowest mean girth (56.9 cm). Other clones, such as RRII 203 and RRIC 100 showed high mean girth on par with RRII 430. Clonal variations with regard to girth increment rate for the four-year block either during the pre-tap or post-tap phases was not significant. However, there was a significant reduction in girth increment in most of the clones in the post-tap block than the pre-tap block. In contrast, RRIM 600 showed significant better girth during the post-tap period than the pre-tap period. RRII 51, RRII 176, and PB 217 maintained similar girth increment rates before and upon tapping. The RRII 400 series clones in general, showed better girth increment rate during immaturity than under tapping.

3.3. Rubber yield dynamics

The analysis of repeated measures on the performance of clones across fortnightly intervals over four years showed significant variation in all components except for clone × year × fortnight interactions (Supplementary Table S1). Further, mean yield based on test-tapping during the immature phase (juvenile yield) showed significant clonal variation (Table 3).

Juvenile yield ranged from 16.64 gtt for RRII 429 to 5.77 gtt for RRII 51. The yield of RRII 422 (13.83 gtt) was comparable with that of RRII 429, and was significantly superior to that of the control clone RRIM 600 (8.91 gtt). Dry rubber yield over four years of regular tapping also showed highly significant clonal variation. Testing of normality of the data showed that data fitted well to the normal distribution (Supplementary Table S2 and Fig. S2). RRII 429 was the highest yielder with average dry rubber yield of 78.70 gtt. The yield performance of RRII 429 was significantly superior to that of RRIM 600 (60.32 gtt). RRII 430 (75.00 gtt) and RRII 422 (74.00 gtt) also recorded high yield comparable to that of RRII 429. RRII 417 (63.08 gtt), PB 217 (63.19 gtt), and RRIC 100 (62.20 gtt) performed on par with RRIM 600. RRII 105 and RRII 51 recorded the lowest yield of 31.70 and 31.80 gtt, respectively. The correlation between juvenile yield and yield at maturity showed a low but significant and positive trend accounting for 21% ($R^2 = 0.21$; $r = 0.46$) agreement between observed and predicted yields (Fig. 2).

The fortnightly yield pattern of clones showed peaks (maxima) and valley (vertex) in an annual cycle following a quadratic trend. The maximum coincided with 23rd and 24th fortnight of the year corresponding to December and extended to the first fortnight of January, while the vertex occurred around the 11th fortnight corresponding to the first half of July (Fig. 3a). Monthly yield pattern showed a progressive increase from June onwards irrespective of clones (Supplementary Fig. S3). The period from April to June was the lowest

Table 3
Yield performance of clones at juvenile stage and over four years of tapping.

Clone	Juvenile yield[a] (g.tree^{-1})	Yield at mature phase[b](gtt)	Latex volume (mltt)[c]	Dry rubber content (%)[c]
PB 217	7.75[bc]	63.19[abc]	208.75[def]	34.62[cd]
RRIC 100	6.71[c]	62.20[abc]	280.69[bcd]	36.35[abcd]
RRII 51	5.77[c]	31.80[d]	200.30[def]	35.57[bcd]
RRII 105	10.59[bc]	31.70[d]	177.91[ef]	37.10[abc]
RRII 176	6.72[c]	36.30[d]	143.98[f]	37.20[abc]
RRII 203	7.71[bc]	57.47[bc]	217.64[cdef]	34.49[cd]
RRII 414	6.29[c]	55.17[c]	208.75[def]	33.03[d]
RRII 417	9.79[bc]	63.08[abc]	243.89[bcde]	39.22[a]
RRII 422	13.83[ab]	74.00[ab]	296.17[bc]	36.40[abcd]
RRII 429	16.64[a]	78.70[a]	426.98[a]	36.23[abcd]
RRII 430	7.95[bc]	75.00[ab]	319.58[b]	38.33[ab]
RRIM 600	8.91[bc]	60.32[bc]	226.54[bcde]	34.81[cd]
SE	2.65	3.59	35.88	1.58
CV (%)	35.90	13.36	17.53	5.36

Values followed by a common letter are not significantly different at 95% confidence level by Duncan's multiple range test (DMRT).
[a] Cumulative yield from ten successive tappings.
[b] Mean of four years of tapping.
[c] Mean of three successive seasons; gtt, g.tree^{-1}.tap^{-1}; mltt, ml.tree^{-1}.tap^{-1}.

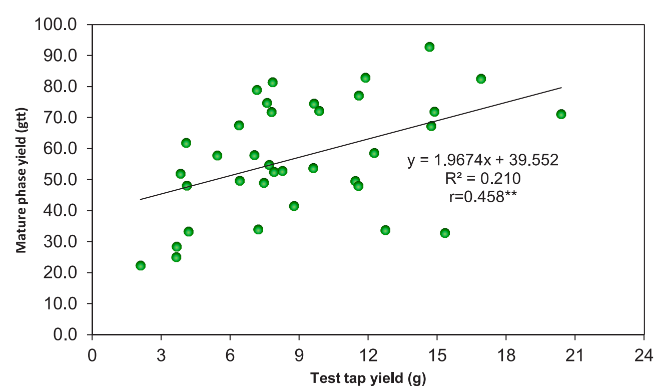

Fig. 2. Relation between immature and mature phase yields showed positive and significant linear relations. Observed and predicted yields were correlated ($r = 0.46$) based on the linear trend ($p < 0.01$), and the coefficient of determination was 21%.

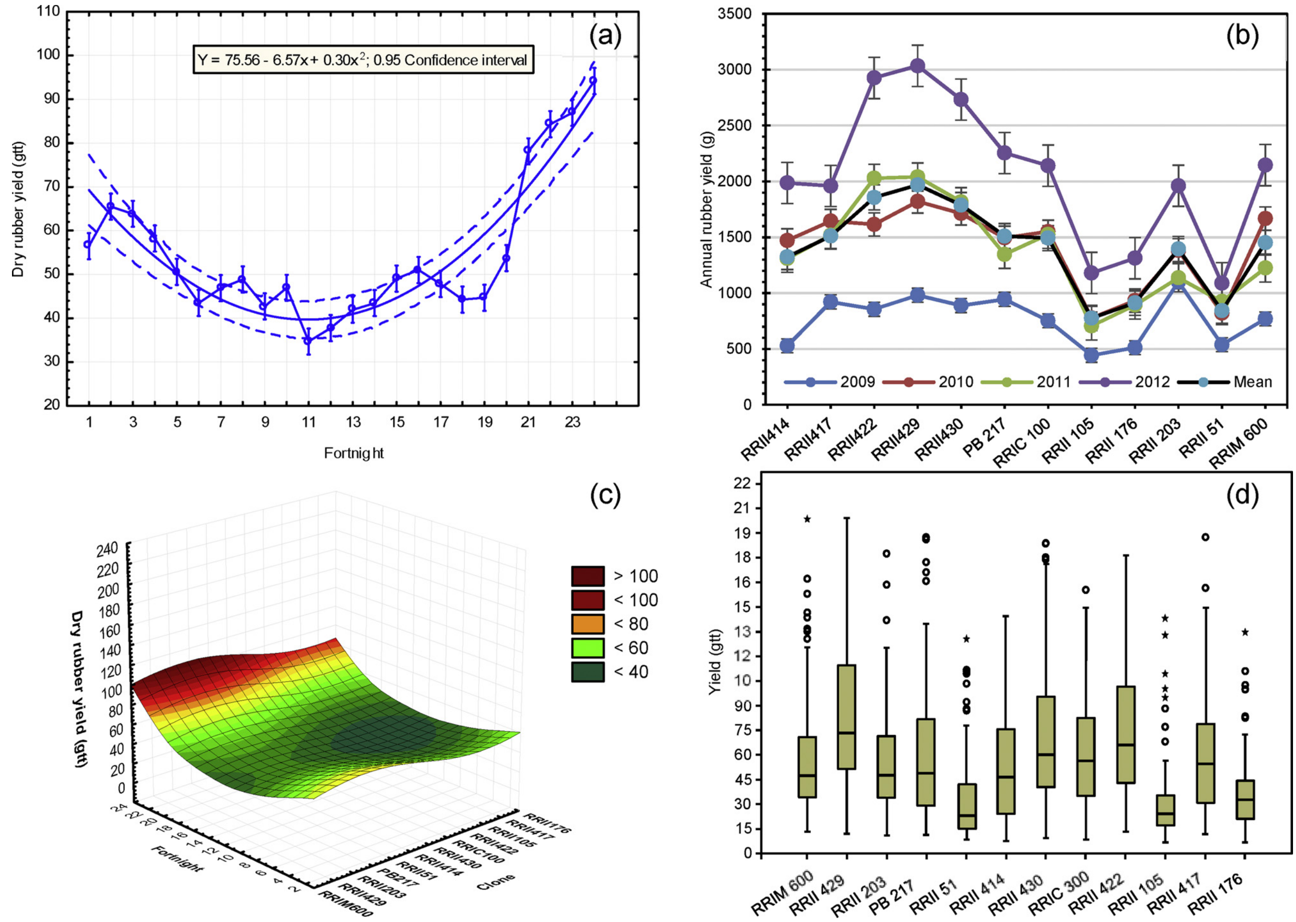

Fig. 3. Annual yield pattern of clones for four years. (a) The fortnightly trend indicates a peak and valley in the yield pattern. The dotted lines indicate 95% confidence band; (b) Cumulative annual rubber yield shows an increasing yield trend over years, and some clones are significantly better yielding than others; (c) The surface plot showing the annual yield pattern of clones, the clones falling in the valley are not suitable for commercial cultivation; (d) Box plots for dry rubber yield, black line within the box indicates media, circles indicate outliers and stars indicate far-out values.

yielding. The yield trend showed a dual peak during July and November with higher yield during the latter phase. Across clones, 50% of the total yield was obtained during the peak-yielding months (November–February), whereas, the contributions during summer (March–June) and monsoon (July–October) seasons were 20 and 30%, respectively. The yield pattern showed a rising trend from first to fourth year of tapping. The top three high yielding clones, RRII 429, RRII 430, and RRII 422 maintained the yield superiority beginning from the first year (Fig. 3b). The surface plot of the temporal yield depicted a comprehensive pattern of clonal behaviour in the region (Fig. 3c). In this, high yielding clones are featured on the elevated surface while the low yielding clones formed a 'valley'. The intraclonal variability for rubber yield summarised in a Tukey's 'box-and-whisker' plot (Fig. 3d) indicated that RRII 429 was the highly variable clone by way of wide interquartile range and highly positively skewed whiskers. This was followed by RRII 422 and RRII 430, among the high yielding clones. RRII 430 recorded two outliers. Lowest variability was shown by RRII 105, RRII 51, and RRII 176, and all of them were the lowest yielders in the study.

3.4. Clone evaluation based on mean yield and temporal stability

GGE analysis of the annual yield pattern revealed RRII 429 as the preferable (ideal) clone for the Eastern-India (Fig. 4). However, the biplot indicated significant instability of this clone as it was found lying away from the average environment axis. Ranking of genotypes based on their yield pattern indicated that RRII 422 and RRII 430 were the

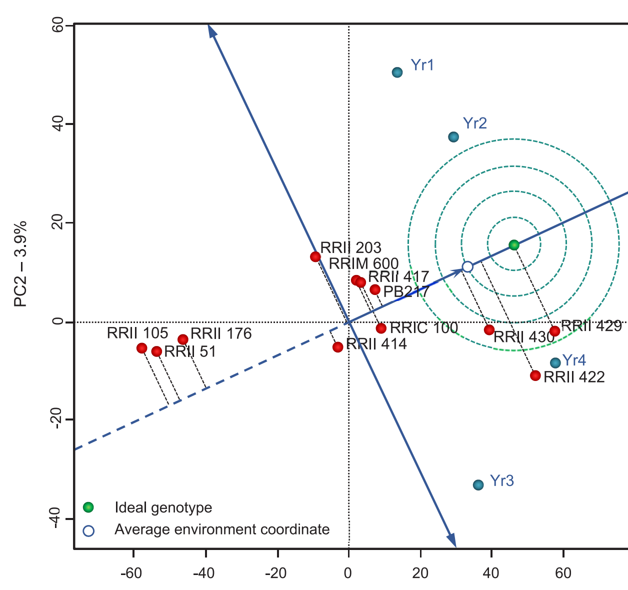

Fig. 4. GGE biplot of clone × year interaction for dry rubber yield among 12 clones. Clones that are right of the line perpendicular to the average environment axis are best suitable for growing in the Eastern Indian region. Genotype ranks fall as they fall back from the ideal genotype.

Table 4
Bark structural features of clones.

Clone	6th YAP		12th YAP	
	Bark thickness (mm)	No. of latex vessel rows	Bark thickness (mm)	No. of latex vessel rows
PB 217	5.34[abc]	5.72	6.73[bc]	7.26[bcd]
RRIC 100	4.99[bcde]	5.33	7.62[ab]	7.72[bcd]
RRII 51	5.33[abc]	5.72	7.64[ab]	6.66[d]
RRII 105	5.67[ab]	6.00	6.74[bc]	8.64[abc]
RRII 176	4.94[cde]	5.33	6.55[bc]	7.80[bcd]
RRII 203	5.97[a]	5.33	7.91[a]	6.99[cd]
RRII 414	5.22[bcd]	6.11	7.42[ab]	7.92[bcd]
RRII 417	5.69[ab]	7.59	7.59[ab]	10.00[a]
RRII 422	5.19[bcd]	4.39	6.98[ab]	7.28[bcd]
RRII 429	4.53[de]	6.06	5.70[c]	9.11[ab]
RRII 430	5.21[bcd]	6.72	6.88[ab]	9.90[a]
RRIM 600	4.47[e]	5.16	7.10[ab]	7.41[bcd]
SE	0.31	0.79	0.78	0.82
CV (%)	7.21	16.70	13.57	12.50

Values followed by a common letter are not significantly different at 95% confidence level by Duncan's multiple range test (DMRT); YAP, year after planting.

next best clones suitable for the region. Further, clones such as PB 217, RRII 417, RRIC 100, RRIM 600, and RRII 203 also be suitable for cultivation but at a smaller scale. They can provide better than average and stable yield as indicated by their closeness to the average environment coordinate. RRII 414, RRII 176, RRII 105, and RRII 51 were identified as clones less suitable for the region.

3.5. Components of yield

The volume of latex ranged from 427.0 mltt (RRII 429) to 144.0 mltt (RRII 176) (Table 3). RRII 430 recorded the second highest latex volume of 319.6 mltt followed by RRII 422 with 296.0 mltt. RRIM 600 recorded 226.5 mltt. RRII 105 and RRII 176 realised the lowest yield of fewer than 200 mltt. All the other clones recorded a moderate latex yield. Clonal differences were significant in the case of DRC also. RRII 417 (39.22%) and RRII 430 (38.33%) recorded the highest DRC. The control clone, RRIM 600 recorded a DRC of 34.81%. Seven clones including RRII 105 recorded significantly superior DRC compared to RRIM 600. Among the RRII 400 series clones, RRII 414 had the lower DRC of 33.03%.

Bark anatomical parameters related to latex yield are given in Table 4. Bark thickness in the 12th YAP ranged from 7.9 mm (RRII 203) to 5.7 mm (RRII 429) with the remaining clones showing intermediate thickness. The variability for number of latex vessel rows was more pronounced than that of bark thickness. RRII 430 and RRII 417 recorded the highest number of latex vessels (9.9 and 10.0 respectively) followed by RRII 429 (9.1). All the other clones were on par with the control clone for this trait.

4. Discussion

4.1. Climatic variables

The rubber tree is naturally adapted to the warm humid climate of the Amazon river basin. Well distributed annual precipitation is essential for its normal growth and survival. In the present study, however, weather data from the experimental site indicated an apparent dry spell of about six months from November–April. During this period, the mean monthly temperature fluctuated between 15 °C and 38 °C and the precipitation was below 50 mm on an average, exposing the rubber trees to intermittent dry spells. The highest maximum temperature had often exceeded above 40 °C during May. However, Brahmam (2002) had observed no apparent damage by scorching of the bark even when the temperature shot upto 45 °C. December was the coolest month with the lowest minimum temperature below 12.8 °C.

Interannual variability for precipitation was wide, and the cumulative annual rainfall over 10 years during the study period ranged from 841.8 mm to 2197.9 mm with an average of 1598.0 mm and a mean number of 75.0 rainy days. The monthly average rainfall was only 133.0 mm, with August having the maximum precipitation of 365.8 mm and December having the lowest average of 5.1 mm. The traditional areas experience rainfall between 2000 and 4000 mm, distributed over 140–220 days, with not more than one to four dry months (Rao and Vijayakumar, 1992). According to Lemmens et al. (1995), a well-distributed annual rainfall of 1500 mm has sometimes been considered as a lower limit for commercial rubber cultivation. However, in favourable soils, a dry season with less than 50 mm rainfall for two to three months (Compagnon, 1986) could be well tolerated by this crop. This indicated that the climatic suitability for natural rubber cultivation in eastern belt of Odisha is within the tolerable limit. However, occasional breach of this limit, particularly in ambient temperature and relative humidity could not be ruled out. Further, no other threat to rubber cultivation in the form of any biotic stress is reported from this region.

The Eastern India region is vulnerable to occasional but severe cyclonic storms accompanied by heavy rains and flooding which usually occur during the northeast monsoon season (September–December). Although the trial was salvaged fully from the damage inflicted by the BOB 03 super cyclonic storm at the third YAP by early preparedness and timely interventions, this event had resulted in a lag in the recoupment of plants, prolonging the period of immaturity and delaying the commencement of tapping.

4.2. Girth and girth increment

All of the modern-day cultivated rubber clones are the result of substantial improvement of crop productivity from a population, known as 'Wickham' base (Simmonds, 1989; Jones and Allen, 1992). Limited to 2397 seedlings that survived out of about 70,000 seeds collected by Sir Henry Wickham in 1876 (Dijkman, 1951) from Santarém, a small region in the upper Amazon in Brazil, the Wickham population was known to have a very narrow genetic base (Prescott-Allen and Prescott-Allen, 1983). However, this population had retained enough phenotypic variability for exercising selection. Since all the clones included in this evaluation were of Wickham base origin, the observed variability for growth could be attributed to their ancestral genetic base rather than their country of origin. The modern clones of RRII 400 series, derived from the cross between RRII 105 and RRIC 100, have exhibited early girth and girth increment from the first year of planting itself. Precocity of RRII 400 series clones in traditional rubber tracts of India was earlier reported by Mydin and Mercykutty (2007). Their female parent, RRII 105 was the most popular clone of India for past five decades with a production potential of more than two tons per hectare per year. However, it was susceptible to wind damage (Vinod et al., 1996a) and diseases such as *Corynespora* leaf spot (Manju et al., 2001). The male parent, RRIC 100, was one of the most widely cultivated clones in Sri Lanka in the 1980s, that covered more than 40% of the rubber lands. This clone was reportedly very vigorous in growth (Samaranayake et al., 1987) and resistant to diseases including *Corynespora* leaf spot (Silva et al., 2002). Early stability for growth in the first three years of planting was observed for the clones RRII 429 and RRII 430 (Meenattoor et al., 2000). The highest tappability of 89% observed for RRII 430 after withstanding the severe storm indicated the growth plasticity of this clone. On the contrary, RRII 429 was significantly affected by the catastrophe and lagged behind other high yielding clones with an average tappability of 52% by 12th YAP. Besides, all of its sister clones, had attained tappability comparable or better than that of RRIC 100 (> 70.0%). In the traditional region, normally, rubber trees mature to commence latex harvest at the age of seven to eight years. Subsequently, about 70% of the trees attain tappable girth by the 8th year and 100% in another two years (Vinod et al., 1996a). Whereas, in some non-traditional areas including Odisha, depending on climatic and edaphic factors, it can take more than 10 years to attain the stipulated growth for tapping (Chandrashekar et al., 1998; Krishan, 2013b).

Although RRII 400 series clones showed very vigorous growth during the immature phase, their post-tap growth rate was relatively lower. Early vigour is recognised as an important factor that determines the yielding ability of rubber clones (Simmonds, 1989) and precocious yielders tend to show more girth retardation under tapping (Wycherley, 1976). The growth pattern observed in the present study corroborates with this. Similar observations are reported for the same clones from other locations (Antony et al., 2010; Meenakumari et al., 2015b). It is noteworthy that, RRII 430 showed consistently superior growth before and after tapping. Growth performance of the new clones revealed that they are highly adaptive to the environmental conditions in Odisha.

4.3. Dry rubber yield and seasonal variations

In the traditional regions, test-tapping in clonal plantations at an early age of four and half years, and before the commencement of regular tapping was reported to show a very high significant positive correlation of 0.9 with yield at maturity (Licy et al., 1998). The high juvenile yield of RRII 429 and RRII 422 observed in the present study reconfirms their precocious yielding capacity as reported by Mydin and Mercykutty (2007). On commencement of regular tapping, data on dry rubber yield for the first four years indicated that the RRII 400 series clones, except RRII 414, were consistently high yielding than the rest of the clones. Among these, RRII 429, RRII 422, and RRII 430 recorded superior yield than RRIM 600, whereas the performance of RRII 417, RRIC 100, and PB 217 was comparable to RRIM 600. There are reports of poor performance of RRII 414 from other non-traditional areas as well (Meenakumari et al., 2011). In general, we could also observe that the initial two to three years of systematic tapping was needed for yield stabilisation and the first four years of yield recording was sufficient for predicting long-term yield (Licy et al., 1998; Mydin et al., 2011; Meenakumari et al., 2015a). The high juvenile yield coupled with high dry rubber yield at maturity of RRII 429, RRII 422, and RRII 430 indicated their prospects for yield realisation under the dry sub-humid climate of the region. However, the degree of association between juvenile and mature yield in the present study was relatively low but positive and significant ($r = 0.46$). Possibly, this could be due to variable performance of different clones in the introduced region and also due to the yield stabilisation that is taking place in the initial years of tapping (Chandrasekhar et al., 2007). The initial yield pattern of these clones was comparable to that was recorded in the traditional region (Mydin et al., 2011). Since all the clones in the study are hybrids (RRII 51 being a half-sib hybrid), all of them had same level of breeding and hence, the adaptation potential displayed by each of these clones can directly be attributed to their genetic makeup (Priyadarshan and Clément-Demange, 2004).

In the traditional rubber tracts of India, the average monthly yield trend shows dual peaks, a first peaking phase during July–August and a second peaking phase from November–December (Rajagopal et al., 2003; Mydin and Mercykutty, 2007). The rubber yield increase begins during May–June period and reaches the first peak during July before falling marginally. The yield increases again during October and reaches the second peak during November. Comparison of two peaks reveal that second peak is slightly taller than the first but the valley between the peaks is seldom shallow (Mydin and Mercykutty, 2007). In Eastern India, however, the yield increase during the first phase occurred during August. Further, the increase was marginal and inconspicuous when compared to the second peak during November–December period. Also, the magnitude of yield surge was lesser than that of traditional regions during the first peak. Occurrence of maximum yield during November–December period was also reported by Krishan (2013b) from this region. This deviant trend in yielding pattern from that of the traditional region is not unexpected from a non-traditional region. In the traditional regions, the modern clones of RRII 400 series showed a contribution 22.18% to the annual yield during the first peak (July–August), while it was 24.24% of the annual yield during the second peak (Mydin and Mercykutty, 2007). In the present case, the yield contribution during the first peak was only 15.30% to the annual yield, while a significant level accounting for 26.63% of the annual yield was received from the second yield peaking phase. In the traditional regions, which experiences both South-West and North-East monsoons, yield surge coincides with the monsoon period, and when ambient temperature falls. While in Eastern India, monsoon period remains usually warmer, which is followed by a drop in temperature as winter approaches. The minimum temperature falling below 15 °C and cool winds providing a relatively moist sub-humid weather during November-January could have favoured increased latex production and flow (Priyadarshan and Clément-Demange, 2004). These observations are, however, different from the trend observed in North Kerala which experiences relatively warmer and weak North-East monsoon, where the peak yielding occurs only once during August–September period coinciding South-West monsoon (Lakshmanan et al., 2014; Meenakumari et al., 2015b).

4.4. Major yield components

Rubber yield in *Hevea* is a complex polygenic trait. Several heritable yield component traits have been identified to strengthen the selection process. Volume of latex, DRC and bark structural parameters are among the major yield components directly or indirectly influencing crop yield. Seasonal variation in yield is primarily the result of fluctuation in the latex volume. The DRC of latex generally varies from 30 to 40% (w/v). The superior dry rubber yield of RRII 429 was largely contributed by its latex volume, whereas RRII 430 exhibited high latex yield associated with high DRC. According to Ho (1975), the cumulative effect of component traits explains upto 40% of the variation in rubber yield. Bark thickness is yet another clonal character that shows association with number of latex vessel rows (Gomez, 1982) and influences the latex yield of different clones. Moreover, these traits are highly heritable (broad sense heritability, $H^2 = 61.6\%$) and showed high genetic advance (Premakumari et al., 1993). RRII 417 and RRII 430 have been reported to possess highest bark thickness and number of latex vessel rows (Meenattoor et al., 2000). The present observations of increase in bark thickness and number of latex vessel rows with age indicated that the climatic constraints are not limiting for good bark regeneration and improved laticifer differentiation.

4.5. Clone x environment interactions

In India, the total share of rubber production from non-traditional areas other than North East accounts to be lesser than ten percent. Expanding cultivation in non-traditional areas has been intensified in the past few decades in order to meet the widening demand-supply gap of this strategic raw material. RRIM 600, the clone recommended under Category I of planting materials for the non-traditional rubber areas including Eastern India, was reported to be performing equally well under both drought prone North Konkan and low temperature stress prone North-East India (Jacob et al., 1999). This clone has been adjudged a consistent yielder all through the sub-optimal areas elsewhere (Priyadarshan et al., 2005). Adaptation of any new crop to ecological niches depends on the magnitude of genotype × environment interactions. Plastic genotypes show better adaptation and survival than non-plastic genotypes (Grenier et al., 2016). However, in commercial point of view, mere survival does not guarantee success of the introduced crop, which in addition requires yield adaptation. Dynamics of yield adaptation of the introduced clones in the Eastern Indian region, indicated a quadratic trend at fortnightly interval with lowest yield coinciding July and the highest yield during December. Similar yield trend was observed in North East India (Vinod et al., 2000). The modern RRII 400 series clones, except RRII 414, were the most preferable clones for the Eastern India region, because they could outperform the recommended clone, RRIM 600. This suggested that the new clones have the ability to tolerate high temperature and associated stresses better and their yield performance is superior to the locally adapted clones identified earlier (Krishan, 2013a,b). The observed 20–30% yield improvement over RRIM 600 combined with vigorous growth and desirable secondary traits is noteworthy. Temporal variations in yield pattern in high yielding *Hevea* clones is quite common especially when exposed to unfavourable climatic conditions (Vinod et al., 1996b, 2010). According to Ceccarelli (1994), genotypes exhibiting high yield potential in otherwise low yielding environs should be preferred when selecting for specific adaptation. RRII 429, the highest yielding new generation clone for North and North-East India (Antony et al., 2010; Das et al., 2015) is the best performer in Odisha also, in spite of its cyclone damage. However, multi-environment trials of the modern clones showed high genotype × environment interaction for RRII 429 whereas RRII 430 showed better stability for latex yield (Meenakumari et al., 2011). Producers perceive yield stability as the most important criterion to minimise crop loss, especially in marginal environments (Ceccareli, 1994; Piepho, 1998). The high growth rate, high tappability, and superior latex yield of RRII 430 observed in this study imply that the yield advantage of this clone may hold equally good or even better in unpredictable environments. The very high wind-fastness is an added advantage of RRII 430 (Krishan, 2014) in minimising damage and allowing more tree stand in ecologically vulnerable areas. RRII 422 on the other hand, is proven for its high summer yield (Varghese et al., 2009; Mydin et al., 2011) and performs well in the dry areas within the traditional belt (Gireesh and Mydin, 2013, Meenakumari et al., 2015b). Moreover, the intrinsic drought tolerance capacity of the above three clones with respect to gas exchange properties and photosynthetic activity has been reported (Sumesh et al., 2011). As regards to RRII 417, even though the yield potential is comparable to RRIM 600, Krishan (2014) reported severe wind damage for this clone in this trial. RRIC 100, which performed on par with RRIM 600 in this study, could be suited for its adaptation to low rainfall as reported from Sri Lanka (Withnage et al., 2007).

4.6. Adaptive plasticity

Regardless of the high performance, it is important to maintain genetic variability in clonal recommendations for commercial cultivation in any new region. Since the RRII 400 series clones are derived from two high yielding parents, RRII 105 and RRIC 100, of which RRII 105 is known to be susceptible to biotic threats (Manju et al., 2001; Narayanan and Mydin, 2012), it is prudent to identify other stable and diverse clones for Eastern Indian region. The present study had offered several choices in this direction, such as PB 217, RRIM 600, and RRII 203 with moderate yield levels. These clones are also reported earlier as above average yielders with multiple stress tolerance from several studies (Vinod et al., 1996a; Priyadarshan, 2003; Diarrassouba et al., 2012; Das et al., 2015). These clones are to be planted in combination with high yielding clones (mixed clonal gardens) for sustaining the genetic homeostasis for tolerance to biotic and abiotic stresses.

At present, the average projected dry rubber yield from clonal plantations in Odisha is 1000–1200 kg ha^{-1} $year^{-1}$ (Krishan, 2013a). The projected yield of the top-ranking clones from the present study is to the tune of 3000 kg ha^{-1} $year^{-1}$. But it is important that, further multi-location on-farm evaluations are required using these high and medium yielding clones before we can confirm the results. Krishan (2015) recently identified a few polyclonal seedling selections from the region with an average yield of 64–75 gtt (approx. 2.5–3 tonne ha^{-1} $year^{-1}$). These facts points to the immense scope of achieving yield levels comparable to that of the traditional belt by incorporation of new planting materials. It should be emphasised that the higher yield obtained in the present study was realised under low input agriculture, without rain-guarding or plant protection measures. Foliar diseases in *Hevea* result in considerable crop loss in the traditional region. In spite of being a high yielder, RRII 429 is less preferred for the traditional areas due to its susceptibility to pink disease. Since Odisha belt is devoid of major biotic stresses, this clone can be a potential promise in realising high commercial yield from this region. However, this clone may be planted in mixed planting preferbly with RRII 430, becuase of its high wind susceptibility. According to World Bank (2014), climate change scenarios by way of unprecedented heat waves, changing rainfall regimes, increase in cyclonic storms, and drought-prone areas getting drier are already impacting agricultural productivity significantly. To increase the global natural rubber production, ecological expansion of rubber cultivation is a major priority addressed by the International Rubber Research and Development Board (IRRDB) member nations, wherein cultivation is rapidly being extended to non-traditional areas faced with several stresses. Currently, when multilateral clone exchange programmes are underway between Asian, African and South American countries, identifying high yielding clones in *Hevea* adapted to stressful environments assumes significance.

5. Conclusion

Despite the cyclonic storms, flash floods and heat waves hitting coastal Odisha, a group of elite rubber clones combining high yield and stress adaptation could be identified from the present study. RRII 429, RRII 430, and RRII 422 were adjudged as the best clones in terms of vigorous growth, high rubber yield and major secondary traits. Among these, RRII 430, the clone well-known for consistent performance, exhibited better adaptive features by way of high girth, highest tappability and yield associated components. RRII 429 was the best, but was susceptible to wind damage. PB 217, RRIC 100, RRII 417, and RRII 203 were the other promising clones with stable performance comparable to that of the control RRIM 600. The results not only indicate the viability of natural rubber cultivation in the region, but also substantial and sustainable yield levels comparable with that of the traditional rubber growing tract could be realised. Therefore, these clones can be recommended for commercial evaluation either as monoclones (RRII 430 and RRII 422) or as mixed clonal gardens. The site selection should, however, be planned and executed with care avoiding areas prone to natural calamities and prolonged stress. Being a predominantly smallholder crop, judicious deployment of clones combining high and stable yield and adaptation to the local environment is essential for non-traditional rubber areas especially considering the long gestation period needed for economic returns.

Author contributions

JRM conceptualised and laid out the trial; JRM, TM, MT and BK, maintained the trial and collected growth and yield data; TM and VT carried out bark anatomical investigations; KKV and TM did data curation, analysis and interpretation; TM, KKV, TG, KKM and JJ wrote and edited the manuscript; all authors have read and approved the final manuscript.

Conflict of interest

None.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.indcrop.2018.02.066.

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