Influence of Climatic Variation on Soybean Yield in Japan and Asia

2014

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Summary

Soybean is one of the most important crops which supplies large part of vegetable protein and oil in the world. Recent global warming trend and associated climate change seem to impact on soybean production. However, the yield formation is rather complicate in comparison with cereal crops, obscuring quantitative effect of weather on the production. This study aimed to reveal the relationship between climatic variability and soybean yield. For the purpose, historical statistic data in Japan and major soybean producing countries of Asia was analyzed and results were verified through an experiment.

Pattern analysis for the soybean yieldin64 years (1948-2012) and 46 prefectures in Japan was conducted which classified yield variation into 9 distinct prefecture groups (PGs) and 9 year groups (YGs) based on the similarity of their prefecture to prefecture and year to year variation. PG formation showed a spatial coherence with north to south variation. Yield fluctuation was largest in the middle part of the country followed by southern part compare to northern part. YG indicates yield has become highly variable in recent period compared to earlier period: as 4 YGs were formed within earlier 42 years (1948-1989; period 1) while 5 YGs were observed within recent 22 years (1990-2012; period 2).

Effects of climatic variation on soybean yield were analyzed for each PG and each period by using monthly climate data. ANOVA results indicated that some of the climatic factors were significantly different among YGs for each PG. Multiple regression analysis of yield with climate factors for each PG supported and quantified the results of ANOVA. Two different regressions were obtain for the above two period indicating precipitation in recent years affected soybean yield less than that in earlier years, while minimum temperature in recent years affected larger. These results suggest that soybean production in Japan become stable against precipitation while damage from warming trend in minimum temperature becomes obvious.

In order to analyze the effect of climatic variability on soybean production in Asia, historical weather data is recommended. However, because most dataset miss solar radiation data, one of the widely used models using daily temperature range was validated to estimate solar radiation. The validation of model based on weather data in Japan showed distinct decadal change of a model coefficient, being affected global warming trend. Although the decadal change together

with seasonal change must be taken into consideration, the application of model is acceptable when available weather data is limited.

Analysis of soybean production, harvested area and yield data of 11 major soybean producing countries in Asia along with USA and Brazil from 1982-2008 indicated that production and yield trend was mostly positive. In general, yield was comparatively higher in the upper latitude temperate countries than tropical humid countries. Correlations were conducted with climate factors and yield dividing the whole period into 3 (1980s, 1990s, and 2000s) to minimize time trend. Yield showed negative relation with annual temperature (average, maximum and minimum) and closer relation with summer temperature. Precipitation also showed negative relation with yield above a certain level (>1500 mm) but not in all 3 periods.

The effect of high temperature and water stress on yield formation was experimentally verified by investigating soybean grown in temperature gradient chamber (TGC). Pollen germination and seed yield were reduced under high temperature (ambient+2^{0}C) and combined high temperature and water stress by 11% to 28% and 22% to 42% respectively. Seed number and Pod set ratio under stress condition was linearly correlated with pollen germination. Therefore, the results on the effect of high temperature support the above statistical analyses.

Although major weather disasters on soybean production are drought and excess rainfall, the results in this study suggests that soybean productivity is being potentially reduced in recent years due to increased temperature in Japan as well as in Asia. If present global warming trend continues, soybean yield might reduce remarkably. Therefore, the development of agronomic and breeding strategy against global warming should be an urgent issue.

Chapter 1

Introduction

1.1. Climate change and soybean yield variation

Historically Soybean (*Glycine max*) was first used as a medicinal plant in ancient China. Now its use has been diversified from as one of the most important oil seed crop to great protein source as soya food to livestock feed, aquaculture and even in the bio fuel industry. Now it is the 3rd most important crop commodity in the world in terms of total world production of 2011 with 262,037,569 metric ton and price around 65,903,601,000 dollars (FAOSTAT, 2014). Although 94 courtiers in the world grow soybean to some extent USA has been world's leading producer of soybean during the past half century with 35% of the total world production (USDA, 2013). The second largest producer of soybean is located in South American with Brazil and Argentina occupying about 27% and 19% of the world production followed by China with 6%. Only four countries in the world produced 82% of global production. Soybean yield also varies highly from one country to another from 3.6 t/ha in to Turkey to 2.9 t/ha in Tajikistan (FAOSTAT, 2014). Apart from difference in technology and biological factors Climate is one important factor that influences yield. Climate factors like temperature, precipitation, solar radiation are intimately related with crop growth and production.

Climate change may manifest itself in two fundamentally different ways: in a change in the mean for example of temperature or precipitation, and in a change in their variance and/or distribution (Rummukainen 2012; Seneviratne et al., 2012). Observations since 1950 show that the length of warm spells and heat waves increased (Barriopedro et al., 2011; Battisti and Naylor 2009; Tebaldi et al., 2006) with more intense and longer droughts and at the same time the number of heavy precipitation events increased. Although Future projections on changes in climatic variation show strong spatial and temporal heterogeneity and remain highly uncertain (Seneviratne et al., 2012) it is likely that the adaptive capacity of crops will be exceeded in many regions (IPCC 2007) and global yield reduction will result corresponding to the most IPCC SRES scenario (Parry et al., 2004)

In respect of mean climate change, annual temperatures will increase by 2.5^0 C to 4.3 ^{0}C in important crop-growing regions of the world by 2080 to 2099 (Christensen et al., 2007) and will exceed the hottest season on record in temperate countries (Battisti and Naylor 2009). Over the next few decades, increasing CO_2 trends will likely increase global yields by roughly 1.8% per decade. At the same time, warming trends are likely to reduce global yields by roughly 1.5% per decade without effective adaptation (Lobell and Gourdji, 2012). By fitting statistical relationships between growing season temperature, precipitation and global average yield for six major crops, Lobell and Field (2007) estimated that warming since 1981 has resulted in annual combined losses of 40 million tonnes or 5 billion US dollars.

Several studies regarding relation between climatic variation and soybean production showed different pattern in different regions. Summer high temperature and growing season accumulated rainfall appears to be the most important climate variables affecting soybean yield variability. Global temperature trend from 1980-2008 caused -3.8 to 1.9 % and precipitation trend resulted -1.5 to -0.2% soybean yield variation (Lobell et al., 2011). Soybean production in the northern Corn Belt region of the United States found that productivity was adversely affected by rising growing season temperatures from 1976 to 2006 (Kucharik and Serbin, 2008). U.S. maize and soybean yields were predicted to decrease by 30% to 46% due to negative influence of rising temperature before the end of this century under the IPCC scenario with the slowest warming trend (Schlenker and Roberts, 2009). Negative relation of summer high temperature with soybean yield was reported in western half of southern Brazil (Ferreira and Rao, 2011) and Argentina (Panelba et al., 2007) using the recent trend from 1970-2002 and 1973-2002 respectively. However, positive relation of growing season maximum and minimum temperature with yield was reported in northern part of china for 1979-2002. Llano et al., 2012 reported positive correlation of annual cumulative precipitation with yield in major soybean producing areas in Argentina, Brazil, USA and China. These studies indicate the significance of soybean yield variation in a spatial and temporal scale with respect to climate.

1.2. Soybean production in Japan and climate influence

Soybeans have been a staple food in Japanese culture since ancient times. Although there is a long history of soy production in Japan, in 2012, domestic production of 235,900 tonnes was only 23 percent of the volume of soy food consumption (FAOSTAT, 2014). For many years, domestic soybean production consistently contributed between three to five percent of total soybean supply (USDA, 2013) under such condition more than 90% of regional demand is fulfilled by import from other countries.

Soybean production and yield vary widely by region in Japan. For example, in 2010, yields in Hokkaido and Saga were more than 2.0 t/ha, but those in Kyoto, Kochi and Oita were about 1.0 t/ha (USDA, 2013). A number of challenges make it difficult to achieve increases in yield and quality of soybean production in Japan. Farmland dedicated to growing soybeans has often been converted from rice paddies which are not ideal for growing soybean. Soybean dry field farming has gradually decreased due to local municipality's farmland improvement policies and changes from soybeans to high profit crops. But most important issue is the climatic influence like typhoon, high temperature and excess precipitation which all presumably cause yield reduction of soybean in Japan but the exact extent and quantitative relation is not known. Knowing the specific relation of climate variables with a crop in a specific region helps to improve yield. Study from US showed that 50% of recent yield increase can be contributed to the recommended management practice (Foulkes et al., 2009) which considers crop-climate relation for defined regions.

Japan has a wide latitude distribution which contributes to the variation of climate from temperate to tropical in the north to south direction. Seasonal difference is also prominent in different latitude. Changing climate study in Japan has clearly shown a general warming of surface temperature over the last 100 yr (Fujibe et al., 2007; Yue and Hashino 2003; Schaefer and Domroes 2009). Annual mean temperatures increased at all over Japan from 0.35 to 2.9° C over the period 1976–2000 (Schaefer and Domroes 2009). Seasonally, the strongest warming trends were observed for winter temperatures and also increasing temperature trends prevailed in summer. Monthly temperature especially monthly minimum temperature showed sharp increase than maximum temperature while day-to-day variability decreased (Fujibe et al., 2007) which are in agreement with the climate change trend in other parts of the world (Fujibe et al., 2007) Regional pattern of climate change is also observed in Japan with higher fluctuation of temperature range and precipitation from south to north (Yoshino 1993). Fujibe (1995) also reported about rising temperature trends at 60 Japanese cities (1891–1992) and their relationship with urbanization: Medium sized cities showed increasing minimum temperatures at a rate of about 1° C/100 years whereas large cities experienced a much stronger warming of 2–5° C /100 years. Therefore frequency of climate change and yield variation study is a topic of great importance for identifying spatial and temporal vulnerability and opportunity of climate factors thereby improving yield.

Previous study (Iwakiri 1976) showed that soybean year to year yield variation increases with north to south direction. Yield showed positive relation with summer temperature (July, August, and September) and negative relation with wetness index. Though such study is pioneer in depicting soybean yield to climate variability it lacks regional scale differentiation and requires updating in the light of recent changing pattern of climate.

1.3. Historical data and solar radiation model evaluation

Solar radiation is one of the most important climate factors that affect crop growth and yield. Rudimentary plant physiological process like photosynthesis depends on the amount of received solar radiation. On another word, crop growth and yield depends on intercepted solar radiation. Therefore solar radiation data is necessary in most crop climate study. Most weather stations in the world do not have the facility and equipment to collect radiation data. In fact the worldwide ratio of weather station that collects weather data to that collects temperature is 1: 500 (Ball et al., 2004). The few that collect data frequently sometimes have gaps due to equipment failure. Again, long term historical data is not available not only in the developing countries but also in the developed countries.

Measurement of solar radiation using empirical relation among easily available climate data like temperature and sunshine duration data is another attractive alternative approach. Different models have been proposed and used for this purpose. Some are based on sunshine duration

(Angstrom, 1924). Some are based on temperature (Bristow and Campbell, 1984; Hargreaves and Samani 1982). Compare to sunshine duration data temperature data are more readily available and as such preferable. In the temperature based model solar radiation, R_s is calculated as product of extra terrestrial radiation (R_a, MJ m^{-2} day^{-1}) and an estimated atmospheric transmissivity coefficient (T_t) as shown in equation-

$$R_s = R_a \times T_t$$

This transmissivity coefficient (T_t) can be calculated using Bristow and Campbell (1984), Hargreaves and Samani (1982), Hunt et al. (1998), Meza and Varas (2000) etc. different model. The accuracy of these models in estimating solar radiation varies with location. However, literature review (Ball et al., 2004; Fletcher and Moot 2007; Liu et al., 2009) showed Hargreaves and Samani (1982) model can estimate solar radiation quite accurately in wide range of locations and it is simple to employ as it only has one empirical coefficient (K_{Rs}) but others (Bristow and Campbell, 1984) have multiple empirical coefficient.

Hargreaves and Samani (1982) set K_{Rs} at 0.16 for inland sites and 0.19 for coastal sites. However, Ball et al., (2004), and Fletcher and Moot (2007) reported that model performance is improved when K_{Rs} value is not fixed (0.16 or 0.19) and calibrated with site. From these studies it can be assume that K_{Rs} can have not only spatial but also temporal variation. This variation can be very beneficial depicting crop- solar radiation that is, climate relation. Studies considering such variability are needed in crop modeling.

1.4. Soybean production in Asia and climate influence

In the 21st century, Meeting up the increasing demand of the largest population under the recent trend of climate change is a huge challenge for Asia. Although the contribution to global production of soybean is very low from Asia (10%) it is the top continent in terms of consumption (USDA, 2013). Asia is characterized by temperate to tropical, subtropical, arid and humid climate. Not only mean annual temperature and precipitation is different from one location to another but also their seasonal variation and pattern. Major soybean producing areas are located mostly in east, south, and southeast and also some parts of central and west Asia.

Soybean is grown in most countries in Asia as a minor crop which is characterized by local climate and soil condition. Yield variation is quite high among the countries and also year to year fluctuation (FAOSTAT, 2014). However, degree and extent may be variable but tendency of warming is noticeable in everywhere in Asia (IPCC, 2007).

In central Asia (North-West China, some parts of Russian federation) 0.7°C increase in mean annual temperature was accompanied with 22% and 33% increase in rainfall from 1961 to 2000.
In West Asia (Iran) significant decrease in frost days and increased precipitation have been reported from 1951 to 2003. In East Asia (China), Warming during last 50 years was more pronounced in winter than summer. Annual rain declined in past decade in North-East and North China; increase in western China, and along south-east coast (IPCC 2007). In east and south east Asia (Japan, Korea, Indonesia, Philippines, and Thailand) increases in mean maximum and mean minimum temperature, decreases in cold nights and cool days were observed with decrease in daily range of maximum and minimum temperature. Correlations between mean temperature and the frequency of extreme temperatures were found in the tropical pacific areas like Philippines, Thailand and southern Japan (Griffiths et al., 2005). In south Asia (India) 0.68°C increase per century was noted with increasing trends in annual mean temperature. Warming was more pronounced during post monsoon and winter with lower number of rainy days along east coast (IPCC 2007). Relation between this type of climate change and crop yield needs to be evaluated which are missing.

Different studies showed that with the upcoming climate change agriculture and crop production of Asia will suffer. Statistical study reveals most crops will face a negative yield impact by 2030 due to changes in temperature and rainfall pattern and soybean yield will be negatively affected in Southeast Asia and West Asia (Lobell et al., 2008). Simulation study of 2071-2100 using IPCC A1B scenario also showed soybean yield damage for South Asia, west Asia even for central Asia (Teixeira, 2011). Most of the studies found in this relation were carried out in global aspect and including many crops. Very few, if any, studies were executed focusing on soybean in major soybean growing countries of Asia with recent trend .

1.5. Experimental evaluation of high temperature effect on soybean yield

With recent trend of climate change in the form of increase in growing season temperature along with extreme event like drought and severe heat stress is anticipated (Dai 2013; Tebaldi et al., 2006; Battisti and Naylor, 2009). Rising CO_2 level has the potential to effect crop production positively but the links are complex (Porter, 2005) even this beneficial effect can be counteracted by the rising temperature level (Ruiz-Vera et al., 2013). High temperature can adversely affect yield by shortening crop duration and perturbation of the physiological processes associated with carbon assimilation (Stone 2001; Craufurud and wheeler, 2009).

The effect of increased temperature on soybean production is highly variable and depends on the extent, duration and crop growth stage in a particular environment. Several control environment study with high temperature stress alone or associated with rising CO_2 level showed reduced soybean yield (Gibson and Mullen 1996; Ferris et al., 1999; Thomas et al., 2010; Vera et al., 2013). In addition, temperature extremes can directly damage plant cells for example heat stress during soybean flowering can lead to sterility by reducing pollen germination and lowering yield (Djanaguiraman et al., 2013; Salem et al., 2007; Koti et al., 2005). Again increase in temperature is not always associated with yield reduction; control chamber experiment with moderate increase in daytime temperature (18−26ºC) during seed filling showed benefited soybean yield (Sionit et al., 1987). This differential response can be explained by the non linear relation of temperature with crop growth rate (Boote et al., 1998). Drought stress also affects soybean yield by altering photosynthesis and other physiological processes and sometimes exerts source and sink limitation simultaneously (Liu et al., 2004; Rotundo and Westgate 2010).

Although drought and high temperature stress often occurs in the field simultaneously, the combined effect is unique and cannot be directly extrapolated from the response to each of the different stresses individually (Rizhsky et al., 2004; Mittler 2006). Until now such type of study is very limited even the few exists are carried under control condition where daytime temperatures were held constant while daily temperature in the fields varies daily and gradually during the growing season. Therefore, it is very difficult to extrapolate the results of temperature controlled experiments to the fields.

Temperature gradient chambers (TGCs) allow the study of temperature effects on crops under field-like conditions, where the inside temperatures tend to keep track with the ambient temperatures (Horie et al., 1995) and our study was designed in such environment so can compare the results with actual field yield data.

1.6. Objectives of the study

Crop climate relation can be studied in different ways: using statistical model with historical trend analysis or using mechanistic or process based model or by control environment experiment. All these methods have their respective merits and demerits. By definition, a model is a schematic representation of the conception of a system or an act of mimicry or a set of equations, which represents the behavior of a system; in such case behavior of crop-climate system. We choose statistical approach using historical trend as it helps to depict a picture in broader scale with certain level of accuracy and probability. Validation and assessment in statistical models do not need field and management data (Lobell and Burke, 2010), and statistical models are more suitable for larger spatial-temporal scales. Limited data can be used in statistical models to catch effects of relative hardly understanding processes.

Very few studies have been carried out relating soybean yield variation to climate variation for Japan using statistical approach and because of the uncertain future climate condition yield forecasting is very difficult. In conjunction with control environment experiment it can be very useful to project yield change. Objective of the study is to firstly classify the regional yield variation of Japan and characterize them in a spatial and temporal scale. Secondly, analyze the variability of climatic factors as corresponding to the spatial and temporal yield variation and establish quantitative relation between yield and climate. Another objective is to analyze the yield variability of major soybean growing countries in Asia with respect to climate change to identify the common denominator of soybean yield. Lastly, purpose of the study was to conduct a control environment experiment mimicking the future climate change condition to verify the effect of climate factor on yield derived from statistical analysis.

Chapter 2

Influence of climatic variation on yield in Japan

2.1. Pattern analysis of year and prefecture

2.1.1. Introduction

Climatic variability is one of the important predecessors of crop yield. It has been stated that as much as 80% of the variability of agricultural production is due to the variability in weather conditions (Petr, 1991; Fageria, 1992). Recent trend of climate change and concomitant impact on agriculture is one of the alarming issues for agronomist. Increasing emission of CO_2 and other green house gases are causing earth surface temperature to rise in a manner that important crop-growing regions of the world will experience 2.5°C - 4.3°C rise of annual temperature by 2080 - 99 (Christensen et al., 2007) accompanied by reduced precipitation (Tebaldi et al., 2006) and regional frequent extreme event (Beniston et al., 2007). As a result global food production will suffer and this response is highly varied between countries for different crop (Parry et al., 2004; Teixeiria et al., 2011; Lobell et al., 2012). Production and yield for all crop including soybean is expected to increase in higher latitude countries while decrease in lower latitude countries (Battisti and Naylor, 2009; Lobell et al., 2008).

Soybean production in Japan is firstly restricted by rainfall. Excess soil moisture around sowing season and heavy rainfall around grain filling season sometimes cause yield reduction. However, quantifying relationship between precipitation and soybean yield is still obscure. Moreover, recent criticisms anticipate future yield reduction caused by global warming (Gibson and Mullen 1996; Thomas et al., 2010; Salem et al., 2007; Tacarindua et al., 2012). Although such experimental results are being accumulated, actual yield reduction of soybean has not yet been reported specially for Japan. Soybean production in Japan is also characterized by several cropping types which are mostly differed with regions. The production in northern part is mainly restricted by low temperature, while that in warmer part by others like crop rotation system.

Again, cultivars are different between cooler northern part and warmer southern regions. Another characterization of soybean production is caused by agricultural policy. The soybean cultivated area varied greatly with government subsidies. These situations suggest that the characterization is quite important to analyze the relationship between climate and soybean yield. Year classification depended on the trend of soybean production and location classification depended on the geographic features and classification based on these features may be adequate to analyze the effect of climatic variability on soybean yield. Pattern analysis has been used by agronomist as a successful tool to characterize crop trait in relation to environment for long time. Accordingly, this study aimed to classified prefectures and years by pattern analysis to recognize the relation.

2.1.2. Materials and method

2.1.2.1. Database and data sources

Soybean production is scattered all over different locations in Japan. The study was based on the soybean yield statistics at the prefecture level. As such total soybean production, area under cultivation and yield data of prefectures were collected from Ministry of Agriculture, Forestry and Fisheries, Japan (MAFF, 2012) which include average yield of all 46 prefectures (excluding Okinawa) in Japan from 1948-2012 (64 years).

2.1.2.2. Data analysis

Standardization of data is a very common and useful technique in statistics that enables comparison of data eliminating certain gross influence and therefore soybean yield was normalized for each prefecture in each year to exclude the effect of yield performance on the cluster analysis. The standardized yield of a raw yield *x* is

$$\text{Standardized yield } = \frac{x - \mu}{\sigma}$$

Where, μ is the mean of the raw yield data, x and σ is the standard deviation of the population. Pattern analysis of the standardized yield data has been carried out using statistical software CROPSTAT which considers GxE interaction. This analysis leads to the formation of clusters which grouped the raw data based on the characteristics of their variation so that clusters have high internal homogeneity (within cluster) and external heterogeneity. It uses a distance based method where a pair wise distance matrix is used as an input of analysis by a specific clustering algorithm leading to a graphical representation where clusters are visually identified; such as dendogram.

2.1.3. Results

2.1.3.1. Yield and production trend

Soybean has been grown in Japan for a long time and detail statistics from the beginning of 1940 has been used to compare total countrywide production and yield variation with respect to the planted area. Overall yield showed fairly positive trend since 1940 whereas production and planted area showed distinctive fluctuating pattern. Total soybean production area in Japan has been fluctuating from 400,000 ha to nearly 100,000 ha since the mid 40's until early 2000 with a highest peak in early 50's and lowest point in the 1994 with 60900 ha production area (Fig 2.1.1).

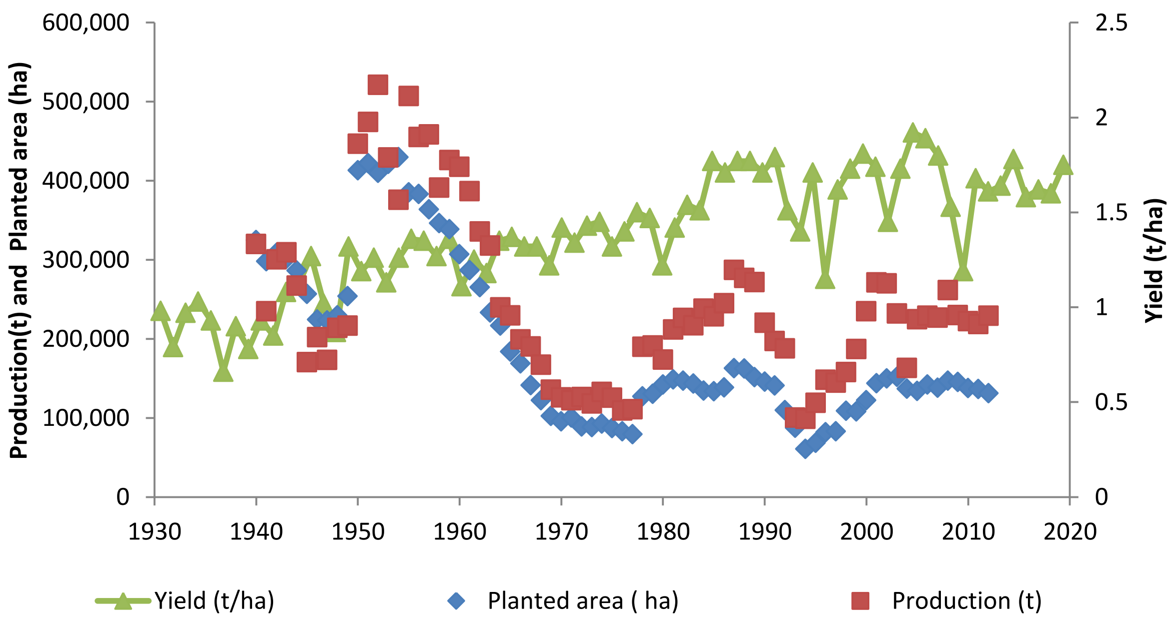


Fig 2.1.1. Soybean production (t), planted area (ha) and average yield (t/ha) trend of Japan.

Production area decrease was quite dramatic during the 50s to 70s but afterward the changing pattern was relatively smooth fluctuating between 60,900 ha to 162,700 ha. As such, total soybean production differs with time corresponding to the production area. However, production did not decrease as sharply as the planted area decreased. The reason behind that was during that time yield became double compare to the early 40s. Although yield has increased significantly over the last 60 years from 1 to 1.8 (t/ha) production areas has not; rather it has decreased. Slow increasing trend of yield with very small fluctuation was observed until 1990. Afterward even though trend was positive the year to year fluctuation was higher. This indicates that in the recent decades when harvest area and production has become comparatively stable yield has become comparatively unstable.

2.1.3.2. Prefecture clusters

Yield pattern analysis reveals that there is a significant soybean yield variation in Japan which can be classified in two dimensions: prefecture wise variation and year wise variation. Depending on the similarity of variation pattern in different prefectures 9 prefecture clusters were formed and prefectures were divided into prefecture group (PG) 1 to 9 (Fig 2.1.2, Table 2.1.1). Formation of these clusters showed distinct spatial coherence as shown in map (Fig 2.1.3). Northern prefectures were classified in some groups while southern prefectures were in some others. These clusters consisted of varying number of prefectures ranging from at least 1 to 10. PG1 to PG 9 were characterized by their north to south distribution. Most north and north-eastern prefectures (15) were classified under 2 clusters as PG1 and PG2 while most south and south-western prefectures (20) were also classified into 2 as PG 6 and PG8. These 4 PGs cover major soybean growing areas of the country and therefore the relative contribution of the rest of the PGs probably is considered lower than these 4 PGs. Among these clusters, PG1 the most northern PG, and PG8 the most southern PG showed comparatively similar yield variation pattern (Fig 2.1.2) as they can be further grouped together to form a bigger cluster based on their similarity. Among the major PGs the difference between PG2 and PG6 may be the highest which coincides with their geographical location one being located in the northern part and other in the southern. Accordingly, PG 5 and 7 showed high degree of similarity with each other and to some extent with PG2 as these 3 can be further groped together like PG1 and PG8.Variation pattern of

Table 2.1.1. Classification of prefectures based on cluster analysis.

Prefecture Group (PG)	Number of prefectures	Prefecture name
PG 1	8	Hokkaido, Ibaraki, Tochigi, Gunma, Saitama, Chiva, Kanagawa, Nagano
PG 2	7	Aomori, Iwate, Akita, Yamagata, Shizoka, Tokushima, Nara
PG 3	2	Miyagi, Fukushima
PG 4	2	Tokyo, Yamanashi
PG 5	4	Gifu, Aichi, Mie, Shiga
PG 6	10	Hyogo, Tottori, Hiroshima, Yamaguchi, Toyama, Fukui, Ishikawa, Kyoto, Okayama, Kagawa
PG 7	2	Osaka, Wakayama
PG 8	10	Nigata, Ehime, Shimane, Fukuoka, Saga, Nagasaki, Kumamoto, Oita, Miyazaki, Kagoshima
PG 9	1	Kochi

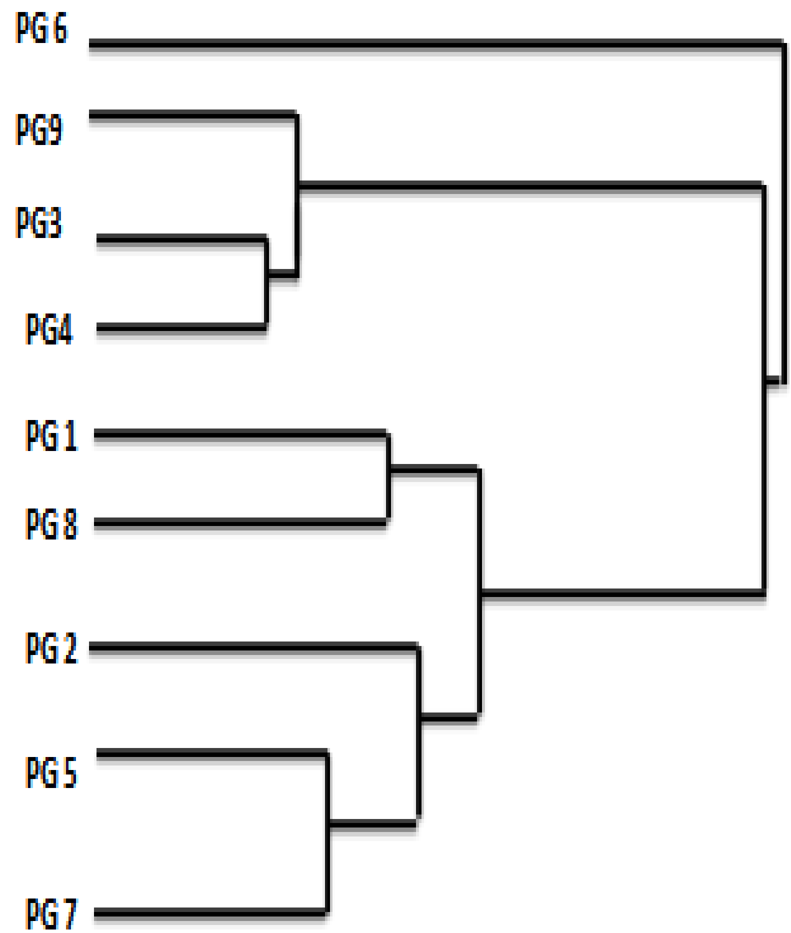


Fig 2.1.2. Dendogram of prefecture group (PG) clusters.

Fig 2.1.3. Locations of nine prefecture groups (PG) on map.

PG3, 4 and 9 had may be the highest degree of similarity with one another and also highest difference with other PGs. From this classification it is obvious that yield variability is higher in the middle part of the country followed by southern part compared to the northern part of the country.

2.1.3.3. Year clusters

Pattern analysis also classified the yield data of 1948-2012 years into 9 year groups (Fig 2.1.4, Table 2.1.2) indicating that yield variation of 64 years can be of 9 types. Formation of year clusters showed that from the beginning of 50s to the beginning of 80s year to year yield variation was comparatively less than 80s onward as only 2 clusters were found from 1948-1980 and 7 from 1980-2012 (Table 2). In fact, we can say for almost 3 decades (24 years) from 50s to the 70s yield variation pattern remain same and almost static (Fig 2.1.1) with some occasional changes (YG1). High degree of yield variation was observed in later 3 decades where decade of 1980s comprised of two YGs (YG4 and 6), 1990s and 2000s each comprised of 3 YGs denoting with time variation of yield is increasing and now even in one decade 3 different pattern is being observed. Year clusters showed that dissimilarity between the mid 1980s yield pattern (YG4) and mid 2000s (YG7) was highest indicating that yield pattern varied quite differently within this 20 years period. Another interesting point to notice was the difference between YG5 and YG6 which was quite high though both consist of the fraction of same decade, 1990s. Similar difference was also observed in 1980s where two parts of same decade showed very different pattern. Yield pattern variation of the most recent decade, 2000s, showed that within a decade there are 3 different patterns (YG6, YG7 and YG 9) and 2 of them might have some similarity (YG7 and YG9) but the third one is very different (YG6).

2.1.3.4. Yield anomalies in prefecture groups (PG) and year groups (YG)

Standardized yield of all the prefecture groups showed fluctuating pattern over the different year groups (Fig 2.1.5). Although yield trend for most PGs is positive over the most YGs some have more fluctuating pattern than others. PG 6 (southern PG) showed highest degree of fluctuation compared to other PGs whereas PG 7 (Osaka, Wakayama) had lowest fluctuation over the YGs. PG1 and PG2 (both consisted of northern prefectures) had similar fluctuation pattern with

Table 2.1.2. Classification of years based on cluster analysis

Year Group	Number of years	Year
YG 1	9	1948,1949, 1950, 1951, 1953, 1954, 1958, 1980, 1993
YG 2	24	1952,1955, 1956, 1957, 1959, 1960, 1961,1962, 1963, 1964, 1965, 1966, 1967, 1968, 1969, 1970, 1971, 1972, 1973, 1974, 1975, 1976, 1977, 1979
YG 3	4	1978,1981, 1982, 1983
YG 4	6	1984, 1985, 1986, 1987, 1988, 1989
YG 5	2	1990, 1998
YG 6	9	1992, 1995, 1996, 1997, 1999, 2000, 2001, 2002, 2008
YG 7	6	1991, 1994, 2003, 2005, 2006, 2007
YG 8	1	2004
YG 9	4	2009, 2010, 2011, 2012

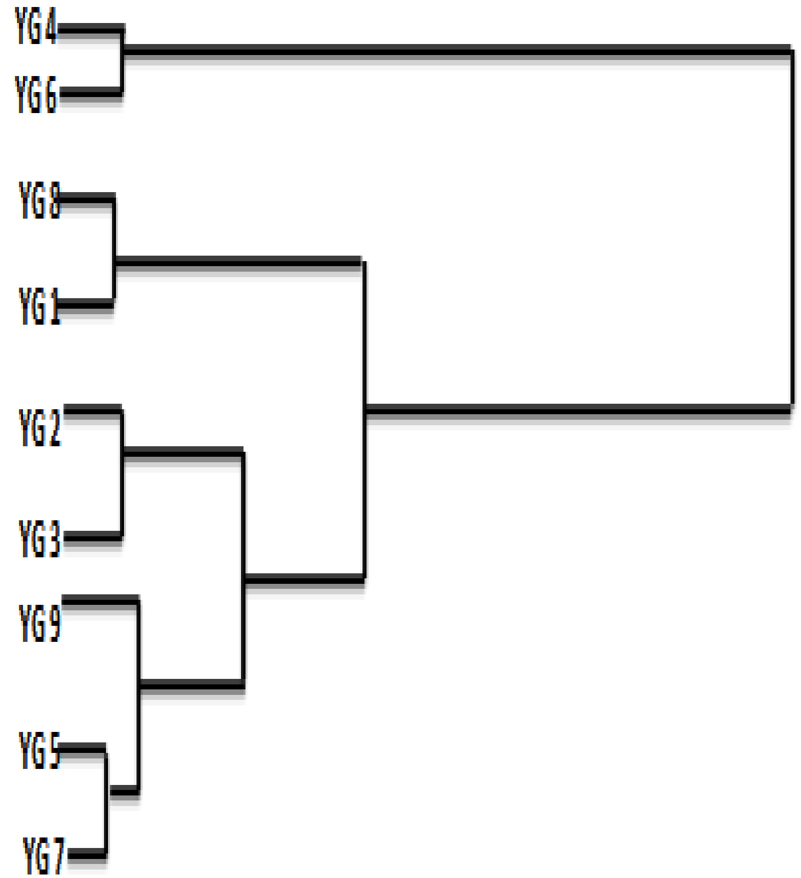


Fig 2.1.4. Yield Cluster dendogram for year group.

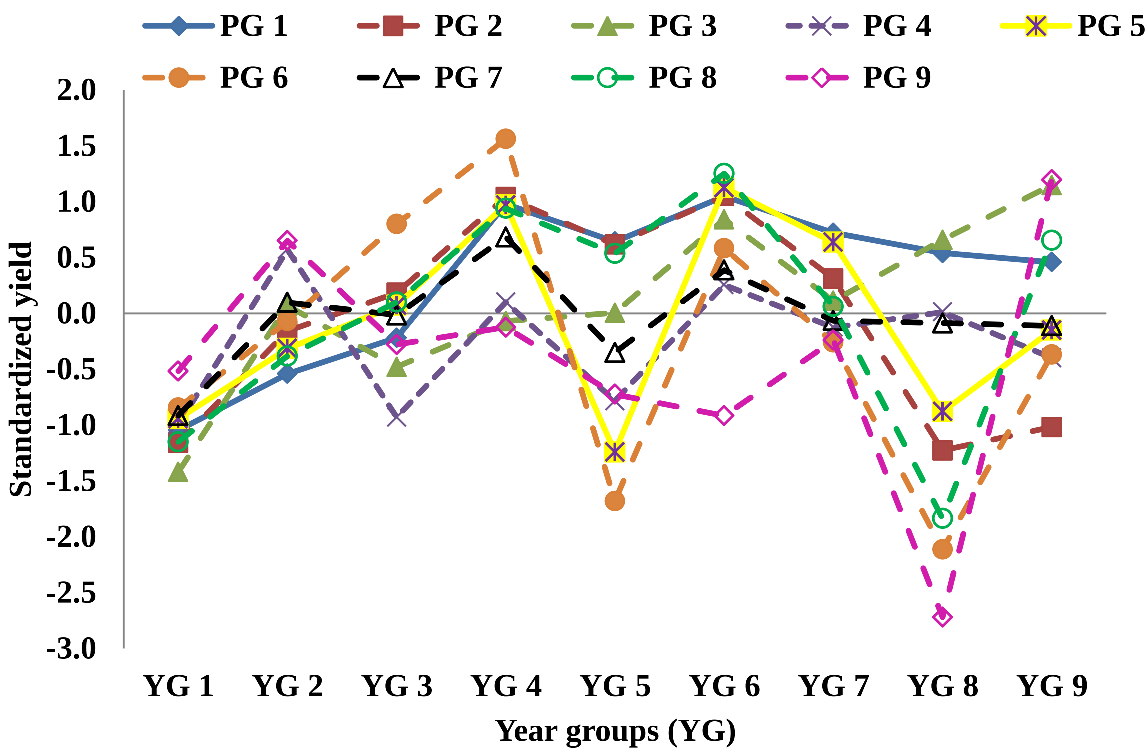


Fig 2.1.5. Soybean yield variation in 9 PGs over the 9 YGs.

negative standardized yield in earlier YGs and positive standardized yield in recent YGs but from 2008-2012 (YG8-YG9) they had opposite pattern where PG1 maintain positive yield and PG2 had negative yield. Similarly PG6 and PG8 (both southern PGs) had similar type fluctuation over most of the YGs until 2009 (YG9) with little difference in YG5 (1990, 1998). Comparison among these 4 PGs (1, 2, 6, 8) reveals that PG1 (northern) and PG8 (southern) had more similarity in yield variation than other similar northern or southern PGs (PG1, PG2 or PG6, PG8). Same can be said about PG2 and PG6 which showed more similarity with each other than PG1 or PG8. However, PG 3, PG 4 and PG 5 had some extent of similarity in yield pattern between them until 2004 (YG 8). Noticeable feature of this yield variation is that in 2008 and onward (YG8 and YG9) where all the PGs had lower (negative) yield PG1 and PG3 had positive yield.

2.1.4. Discussion

Yield pattern analysis showed that soybean yield trend in Japan is location specific and time specific and this variation is quite high which signifies that in a particular year yield improvement or loss in a particular location does not represent or correlate with the whole picture and to form any sort of relation between crop yield and environmental factors these needs to be considered. In this aspect location specific (PG wise) and time specific (YG wise) comparison is preferable and easier to explain the variability.

PG classification showed that 15 northern prefectures which covers around 60,423 ha of planted area (MAFF, 2013) can be grouped in to 2 groups (PG1 and 2) whereas 20 prefecture of south which covers around 42,484 ha planted area (MAFF, 2013) can be grouped into 2 (PG6 and 8). This indicated that variation per planted area is higher in southern part than northern prefectures this is also evident when we compare only PG1 (38,043 ha) and PG8 (27,829 ha). However, in the middle part of the country variation is highest where PG3, 4, 5, 1 and 8 all occupies around 44,540 ha of planted area which is almost twice the variation that is observed in the southern part.

Year yield cluster exhibited that different PG had different year to year variation in yield. This variation frequency has become remarkably higher in the recent years than earlier time in all the PGs except may be one (PG7) where variation is comparatively stable. There is sequential pattern of increase and decrease in the yield during mid 1980s to the mid 2000s when yield become highly variable in almost all PGs (Fig 2.1.5). However during this whole period PG1 and PG2 (northern PGs) maintain very high yield consistently whereas yield in PG6, PG8 (southern PGs) and others varied significantly. In fact, if we consider the entire study period (1948-2012) on average the highest yielding PGs will be PG1 followed by PG8 and followed by PG2 which encompasses major planted area of the country. Conversely, PG4, PG9 and PG7 (in total 5 prefectures) had on average lowest yield over the whole study period. Yield decrease and increase in PG6 during the study period coincides with total yield increase and decrease which can be interpreted as the yield variation during this whole period can be mostly contributed to the variation of PG6 and party due to PG8 and other PGs. In other word, yearly yield variations mainly arise due to the variation of yield in southern and southwestern areas.

In brief this study provides a generalized idea of soybean yield variation pattern over a broad period of time in different prefectures and points out the lower and higher yield fluctuating areas of the country and also provides idea about yield variation pattern over years. This classification of yield variation can be helpful to derive some relation of soybean yield with climatic factors since we know climate in northern and southern part of Japan is distinctly different and may play an important role in shaping the yield pattern.

2.2 Relation of climate and yield anomalies

2.2.1. Introduction

The relation between climate and crop yield has been a major topic of study for the agronomist for a long time and with the future climate predicament anticipated by IPCC (2007) and this aspect of study has become crucial more than ever for assessing and ensuring future food security.

Soybean is the most widely grown legume in the world which has been extensively used as edible oil, food bean and animal feed. Although there is a long history of soybean production in Japan, the supply is much lower than the domestic demand according to the statistics of Japan's MAFF (2008-2012). This difference in demand and supply is likely to increase in future for the entire southeast Asian region (Rosegrant et al., 2001). One of the major reasons for soybean yield limitation or failure in Japan is the climatic variation and extreme events.

The task of predicting crop responses to climate would be easy if crop yield were determined by a single and simple biological process. The reality, of course, is more complex. Crop growth and reproduction are governed by many interacting processes and this demands an enormous challenge to efforts at prediction. One approach is to rely on the statistical relationships that emerge between historical records of crop production and weather variations (Lobell and Burke, 2010). Such type of study (Zhang and Huang, 2012; Ferreira and Rao, 2011; Llano et al., 2011; Penalba et al., 2007, Tannura et al., 2008) provides important information identifying major climatic factors relating a particular crop in a defined geographical location.

Highly variable soybean yield in different parts of Japan along with year to year variation has been a common feature of soybean production in Japan for long time. For example, in 2010, yields in Hokkaido and Saga were more than 2.0 mt/ha, but those in Kyoto, Kochi and Oita were about 1.0 mt/ha (USDA, 2013). In order to draw a relation between soybean yield and climatic factors, the yield needs to be characterized in a temporal and spatial scale to minimize the variations that arises from non climatic factors. Therefore we used pattern analysis to classify soybean yield for last 64 years in 46 prefecture of Japan into two types of groups: prefecture groups (PGs) based on their prefecture wise variation and year groups (YGs) based on their yearly variation (in our previous study). The objectives of this study is to (1) establish relationship between climate factors and yield under specified spatial temporal region (2) analyze monthly variability of climate factors like average, maximum and minimum temperature, sunshine duration and precipitation in that defined spatial temporal scale (PGs and YGs) in relation to yield variations derive the influence of climate on observe yield variation.

2.2.2 Materials and methods

2.2.2.1. Data collection

Soybean average yield data were collected from Ministry of Agriculture, Forestry and Fisheries, Japan (MAFF, 2013). These data were selected from 46 prefectures (excluding Okinawa) in Japan from 1948-2012. Meteorological data for corresponding 64 years were collected from Japan meteorological agency (JMA, 2013). Database was formed with monthly average Temperature (Tav, °C), monthly maximum temperature (Tmax, °C), monthly minimum temperature (Tmin, °C), monthly average precipitation (ppt, mm) and monthly average sunshine duration (Sd, hr) data for each prefecture.

2.2.2.2. Data analysis

The pattern analysis study in chapter 2.1, soybean yield data were classified in some clusters which were mentioned as prefecture groups (PG) and year groups (YG). For this study we divided the 9 YGs into 2 periods: one having relatively lower fluctuation in yield; period 1 (1948-1989) and another with very high fluctuation; period 2 (1990-2012). Both periods comprising of four YGs: period 1 (YG1, YG2, YG3, YG4) and period 2 (YG5, YG6, YG7, YG9). It should be mentioned that we excluded YG 8 from the above study because it was just one year (2008) which had severe detrend yield or poor yield because of extreme weather like typhoon.

We considered the monthly climate condition of 1970-2000 as a baseline climate and calculated deviation of the monthly climate (temperature, precipitation, sunshine duration etc.) data from normalized data of 1970-2000 (30 years) for each prefecture provided by JMA and compared the significant difference in the deviation between YGs in each period by conducting analysis of variance (ANOVA). Then in order to estimate the combined effect of the climatic variables in the final yield of the crop, a stepwise multilinear regression model was used (Draper and Smith, 1981) which was performed with statistical software SPSS V.16. This statistical model selects the predictor variables according to their levels of importance and when they produce a significant contribution to the variance is accounted for in the regression. Each predictor variable is evaluated for its individual significance level before being included in the equation and, with each addition; each variable within the equation is then evaluated for its significance as part of the model. A variable is included and retained in the equation if it is significant at the 95% confidence interval level. Thus we obtained 2 equations for each PG only except PG 4 where in period 2 there was no significant correlation among the variables and no regression equation was obtained.

2.2.3. Results

2.2.3.1. Climate change in two periods in relation to yield anomaly change

Japan has wide range of latitude and the climate varies widely from one region to another along with the latitude. Most parts of the country have four distinct seasons. Spring comprising of March, April, and May, summer comprising of June, July, and August while Autumn months being September, October, and November; and winter months being December, January, and February. Two primary factors influencing Japan's climate are location near the Asian continent and the existence of major oceanic currents like the warm Kuroshio Current (Japan Current); and the cold Oyashio Current (Okhotsk Current).

Average annual temperature varies from 9^0C -23^0C from northern part to the southern part of Japan with immense variation between summer and winter temperature as observed on the last 30 years (1970-2000) normalized data. Summer monthly average temperature varies from 20^0C -28^0C from northern to southern part while winter average temperature varies from -2.5^0 to 10^0C, (JMA, 2013). Monthly deviation from the standardized data of last 30 years (1970-2000) reveals some distinct trends in two periods.

Monthly average temperature (Tav) anomalies for two periods showed different changing patterns in summer, winter and autumn (Figs 2.2.1–2.2.9). This deviation range are lower in period1 from 0.5^{0}C to –1.5^{0}C variation from standard value (1970-200) and 3^{0}C to –3.5^{0}C in period 2 in all PGs. Tav deviation seems to be mostly positive in period 2 implying higher than standard Tav in most PGs while the reverse is observed for period 1(Fig 2.2.1). In general, Monthly Tav increased from earlier years (YG1, YG2) to comparatively recent years (YG3, YG4) in period 1 in all PGs. Aug and July Tav Showed statistically significant (0.05% level) changes among different YGs in Both periods for most of the PGs.

For most PGs in period 1, there was distinct increase from standard in Aug Tav of YG4 compare to other YGs and in almost all PGs while in period 2 Aug Tav of YG9 (2009-2012) decreased noticeably in almost all PGs. Thus consistent increasing trend of summer average temperature (Aug) is observed during the whole study period until the most recent years (YG9). Conversely, winter average temperature particularly for the Month of Feb and March remain considerably lower than standard in period1 in most locations while in period 2 Feb (sometimes March) Tav showed marked increase from standard in most locations like PGs of 5, 6, 7 where this change was statistically significant. Thus increasing trend of winter average temperature is observed in last two decades (period 2). However, changing patterns among the YGs are not consistent. Autumn Temperature (Tav of Sep, Oct, Nov) is lower than standard in period1 but higher in period 2 at all locations. Tav variation pattern may be similar from north to south PGs but Standard temperature is very different like close to 25^{0}C in PG1 and 27^{0}C in PG8. This indicates that although summer Tav had been increasing from the last six decades (period 1 and 2) winter and autumn Tav is increasing from only last two decades significantly.

Monthly maximum temperature (Tmax) anomaly study reveals that July, August, September and sometimes February are the months that showed statistically significant variation at least in three PGs in period 1(Figs 2.2.4, 2.2.8, 2.2.9) and six in period 2 (Fig 2.2.2, Figs 2.2.4 –2.2.9). Feb Tmax is markedly higher than standard in YG1 (period 1) and YG 5 (period 2) in most locations. In period 1, July-August Tmax were lower than standard in YG1 which in later years like YG4 increased strikingly whereas in period 2 Tmax was higher in YG5 or 6 and lower in YG9 in most locations. This denotes an increasing trend of Summer Tmax (July-August) during the last six decades until the very recent YG9 which coincides with Tav trend mentioned earlier and an increasing trend for winter as well.

Like Tav and Tmax, Tmin also showed higher degree of deviation in period 2 having mostly positive deviation in most locations than peiod1. PG1 to PG6 (Figs 2.2.1-2.2.6) exhibited similar changing pattern in period1 with lower than standard Tmin for the month of February (sometimes in March) and October (sometimes in September) and higher than standard in period 2. Statistically significant changes were observed for the month of August in PG1 and PG2 in period 1 while in period 2 for the month of October and November. This indicates autumn and winter Tmin increased from period 1 to period 2 particularly in northern and eastern territory.

In general, this warming trend between YGs in period 1 showed to improve yield in most of the locations (PG1, PG2) and decrease yield among YGs in period 2 when compared with yield anomaly of the YGs.

Total annual rainfall varies from 1107-2266 mm from northern part to the southern part of Japan. Highest monthly average precipitation occurs in the months of June, July followed by September and August (JMA, 2013). In general, there was significant (5% level) variation in winter rainfall among the YGs in period 1 and period 2 (Fig 2.2.7 and Fig 2.2.8). In fact, December, January in period 1 and February in period 2 had significant variation in almost all locations. Apart from that, only PG1, 2 and 6 showed discernible change in summer (June, July) and autumn (September and October) rainfall trend in period 2 (Fig 2.2.8). In period 1 summer rainfall tends to be very high compare to standard while in period 2 it tends to be lower than standard in most PGs which is clearly visible in PG 4, 5, and 6. Autumn rainfall pattern shows completely opposite trend to summer with lower than standard rainfall in period1 and higher than standard in period 2. This trend exists in all the PGs but particularly noticeable in PG1, 2, 4, 5. These analyses reveal an increasing trend of autumn rainfall while summer rainfall is decreasing simultaneously from period 1 to period 2.

In general, increasing rainfall trend among YGs in both periods showed to lower yield though to some lesser extent in period 2 when compared with yield anomalies of the YGs.

Total annual sunshine duration varies from 1740 -1935 hr from northern part to the southern part of Japan. Highest monthly sunshine duration occurs in the months of August, followed by May, April, and July. Therefore, average sunshine duration for summer and spring months are almost same and higher than autumn and winter (JMA, 2013). On average, summer sunshine duration is higher in period 1 and lower in period 2 (Figs 2.2.1– 2.2.9) compare to standard in all locations. Most outstanding evidence was observed in PG2 and PG3. In almost all locations except for PG 4 autumn sunshine duration is decreasing as period 2 exhibited lower deviations than period 1 from standard. However, most significant variation of sunshine duration was observed during winter in the month of December, January (PG2, 3, 6, 8) in period 1 and in February (PG1, 3, 4, 7, and 9) in period 2.

In general, increasing sunshine duration among YGs in both periods tends to improve yield when compared with yield anomalies of the YGs and variation in sunshine duration seem to affect yield in almost all PGs.

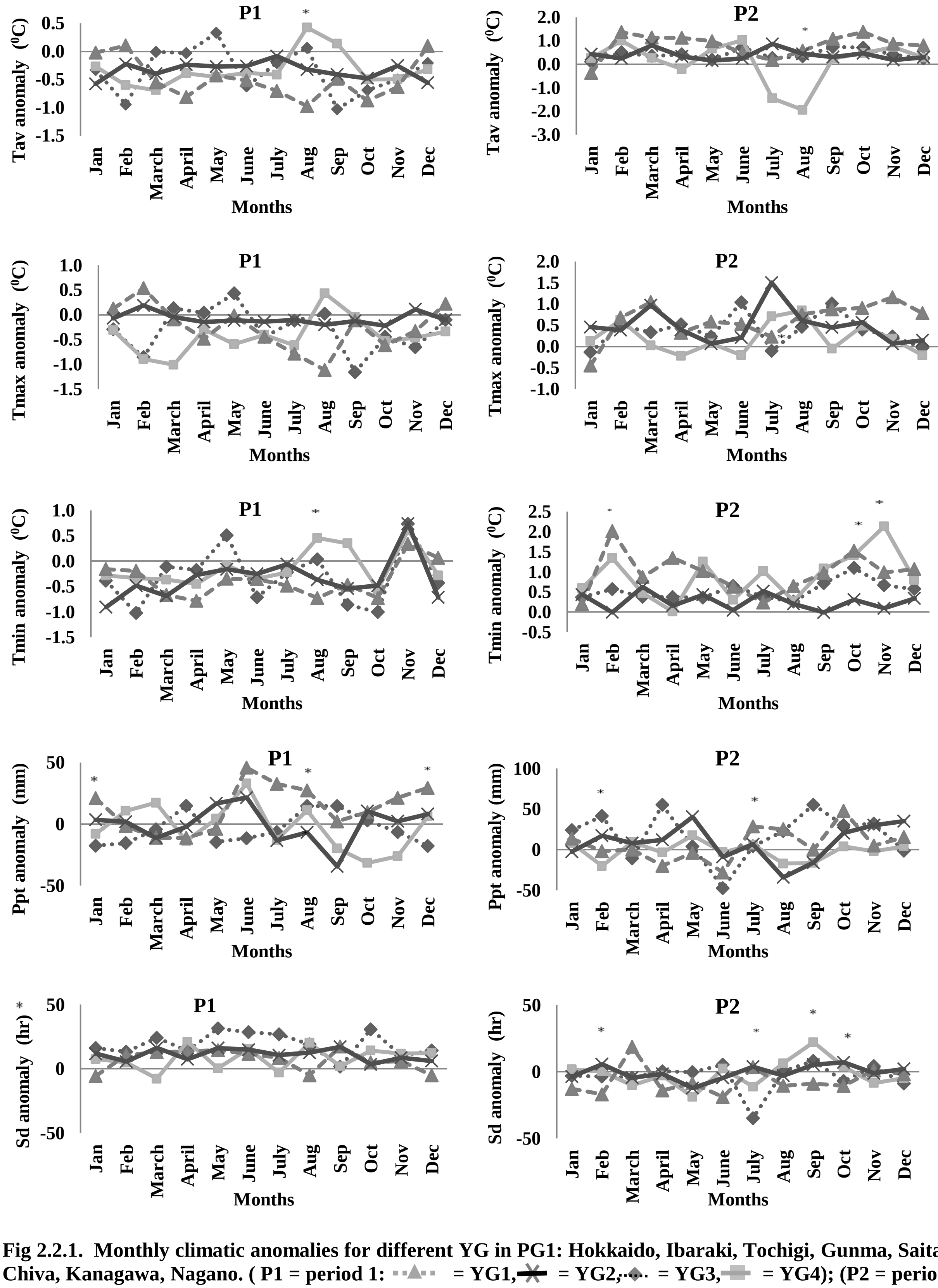


Fig 2.2.1. Monthly climatic anomalies for different YG in PG1: Hokkaido, Ibaraki, Tochigi, Gunma, Saitama, Chiva, Kanagawa, Nagano. (P1 = period 1: = YG1, = YG2, = YG3, = YG4); (P2 = period 2 : = YG5, = YG6, = YG7, = YG9).

***indicates monthly variation is significant at 5% level.**

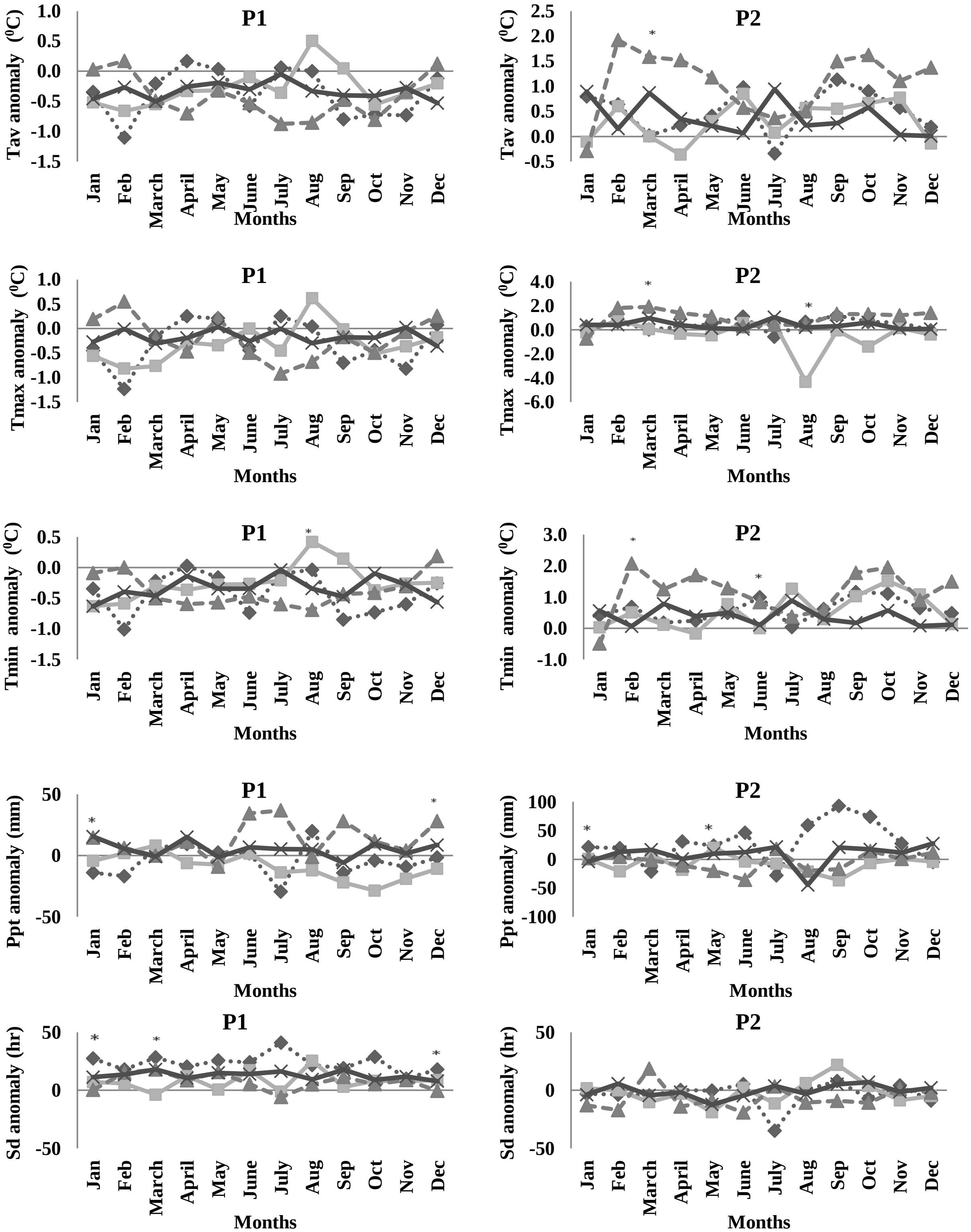


Fig 2.2.2. Monthly climatic anomalies for different YG in PG2: Aomori, Iwate, Akita, Yamagata, Shizoka, Tokushima, Nara. (P1 = period 1: = YG1, = YG2, = YG3, = YG4); (P2 = period 2: = YG5, = YG6, = YG7, = YG9).

***indicates monthly variation is significant at 5% level.**

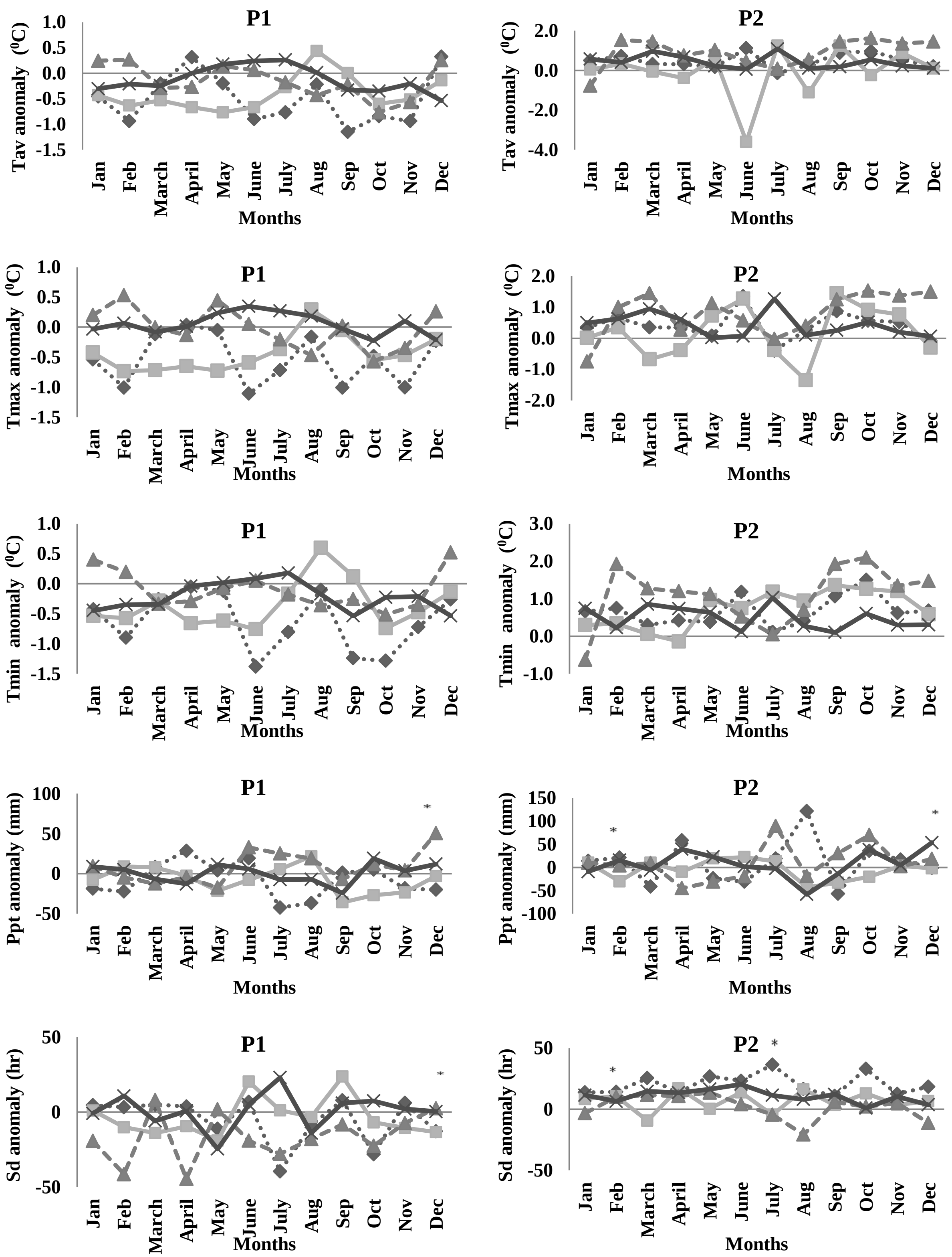


Fig. 2.2.3. Monthly climatic anomalies for different YG in PG3: Miyagi, Fukushima. (P1 = period 1: = YG1, = YG2, = YG3, = YG4); (P2 = period 2: = YG5, = YG6, = YG7, = YG9).

***indicates monthly variation is significant at 5% level.**

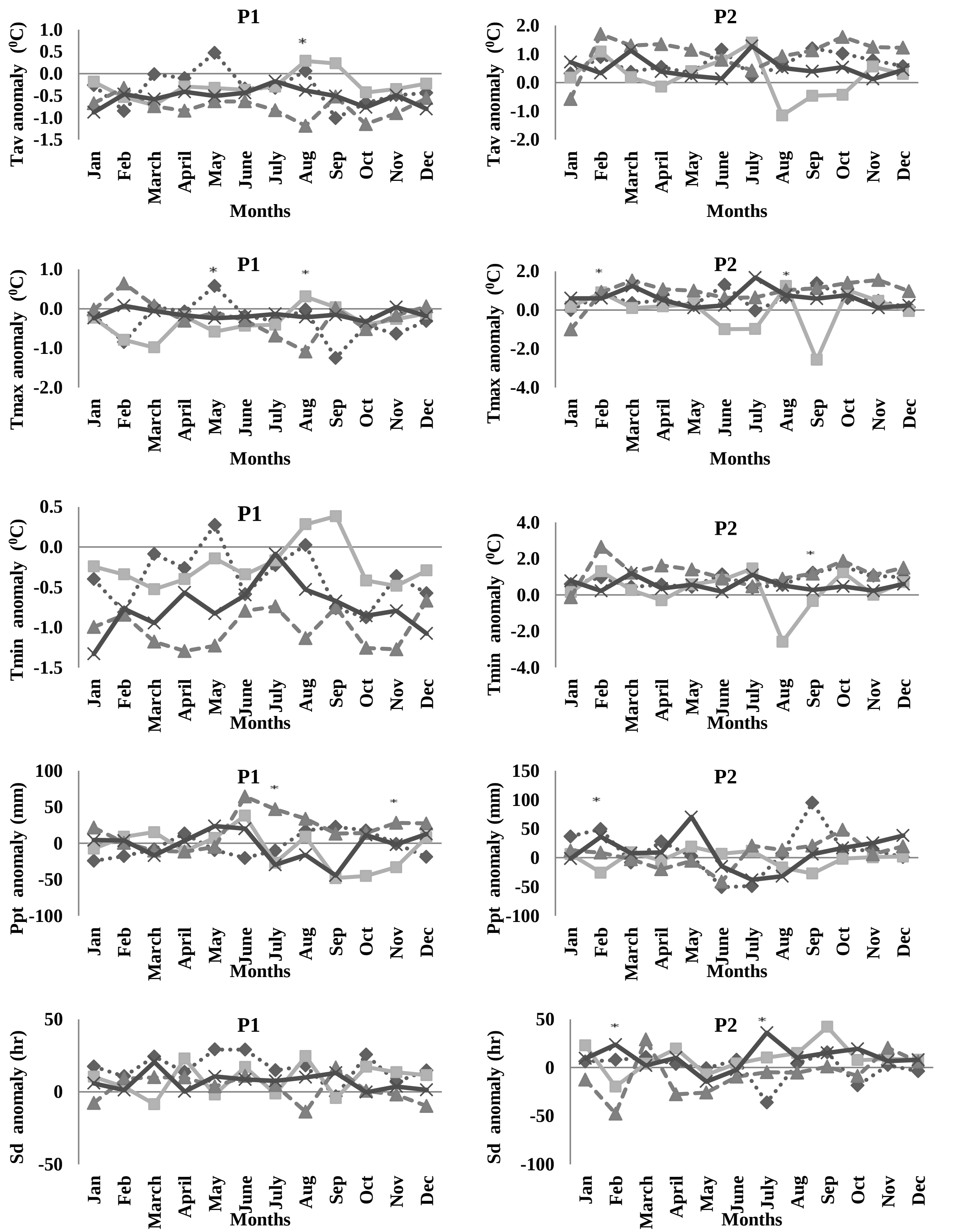


Fig. 2.2.4. Monthly climatic anomalies for different YG in PG4: Tokyo, Yamanashi. **(P1 = period 1: = YG1, = YG2, = YG3, = YG4); (P2 = period 2: = YG5, = YG6, = YG7, = YG9). *indicates monthly variation is significant at 5% level.**

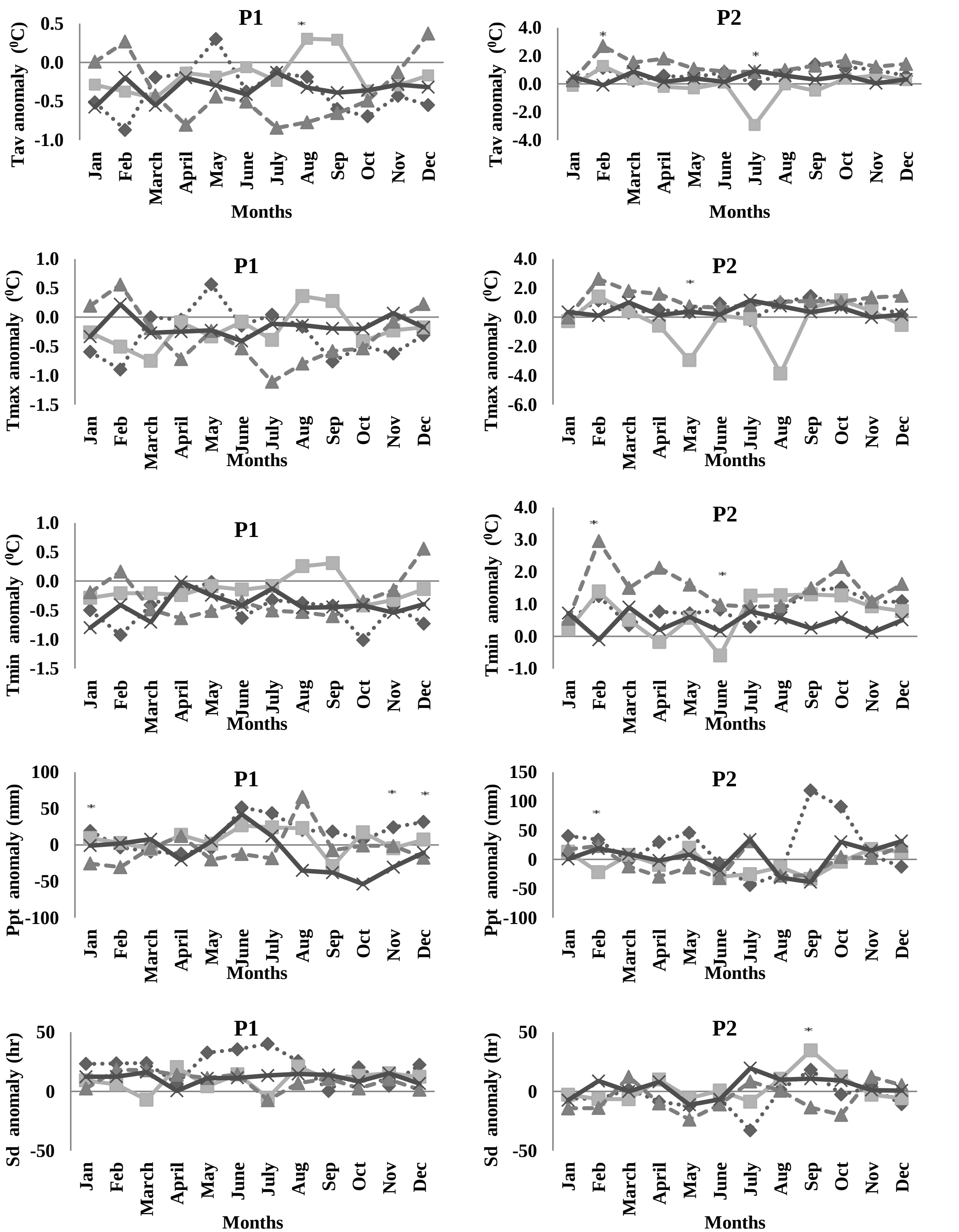


Fig. 2.2.5. Monthly climatic anomalies for different YG in PG5: Gifu, Aichi, Mie, Shiga. (P1 = period 1: = YG1, = YG2, = YG3, = YG4); (P2 = period 2: = YG5, = YG6, = YG7, = YG9). *indicates monthly variation is significant at 5% level.

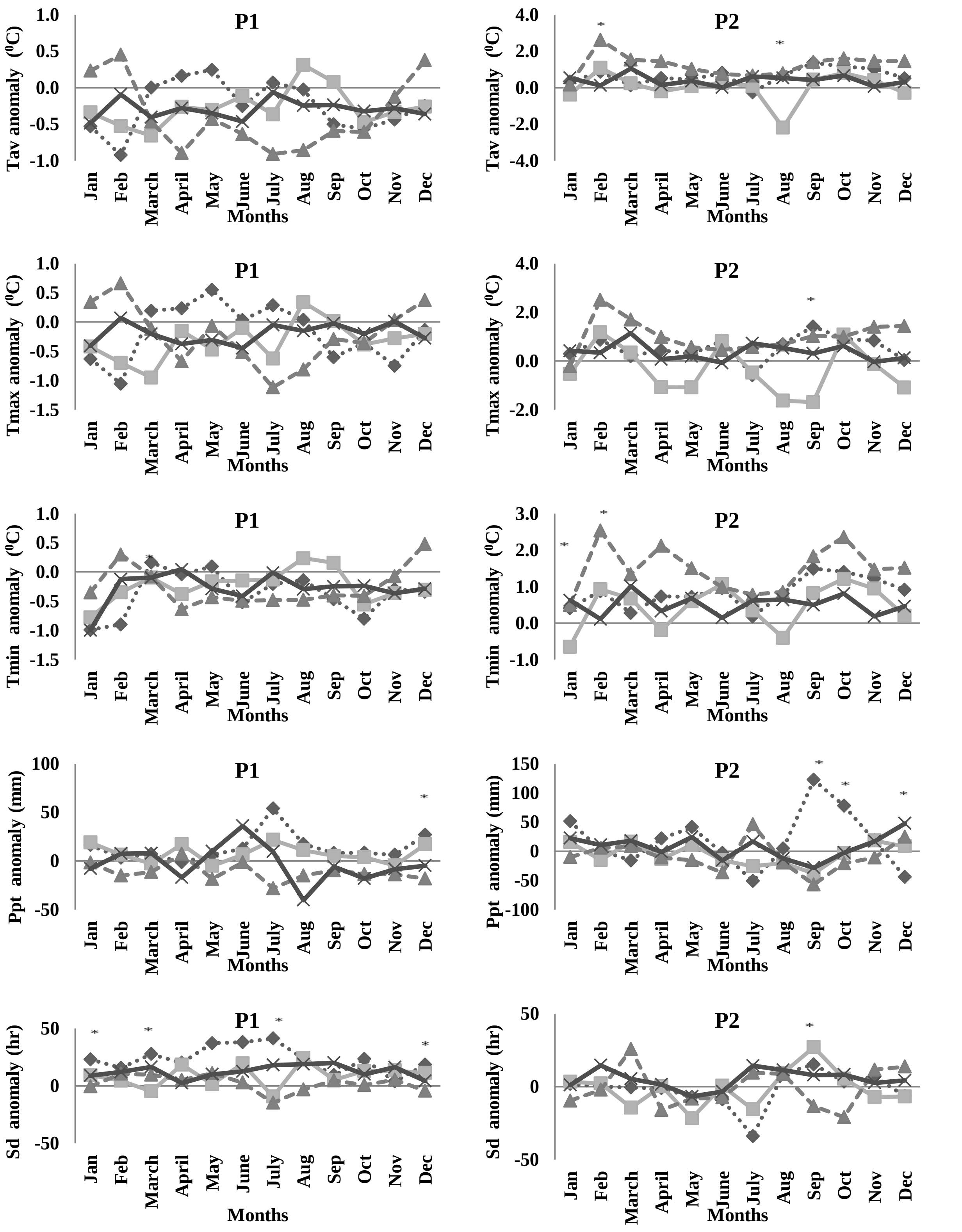


Fig. 2.2.6. Monthly climatic anomalies for different YG in PG6: Hyogo, Tottori, Hiroshima, Yamaguchi, Toyama, Fukui, Ishikawa, Kyoto, Okayama, Kagawa. (P1 = period 1: = YG1, = YG2, = YG3, = YG4); (P2 = period 2: = YG5, = YG6, = YG7, = YG9).

***indicates monthly variation is significant at 5% level.**

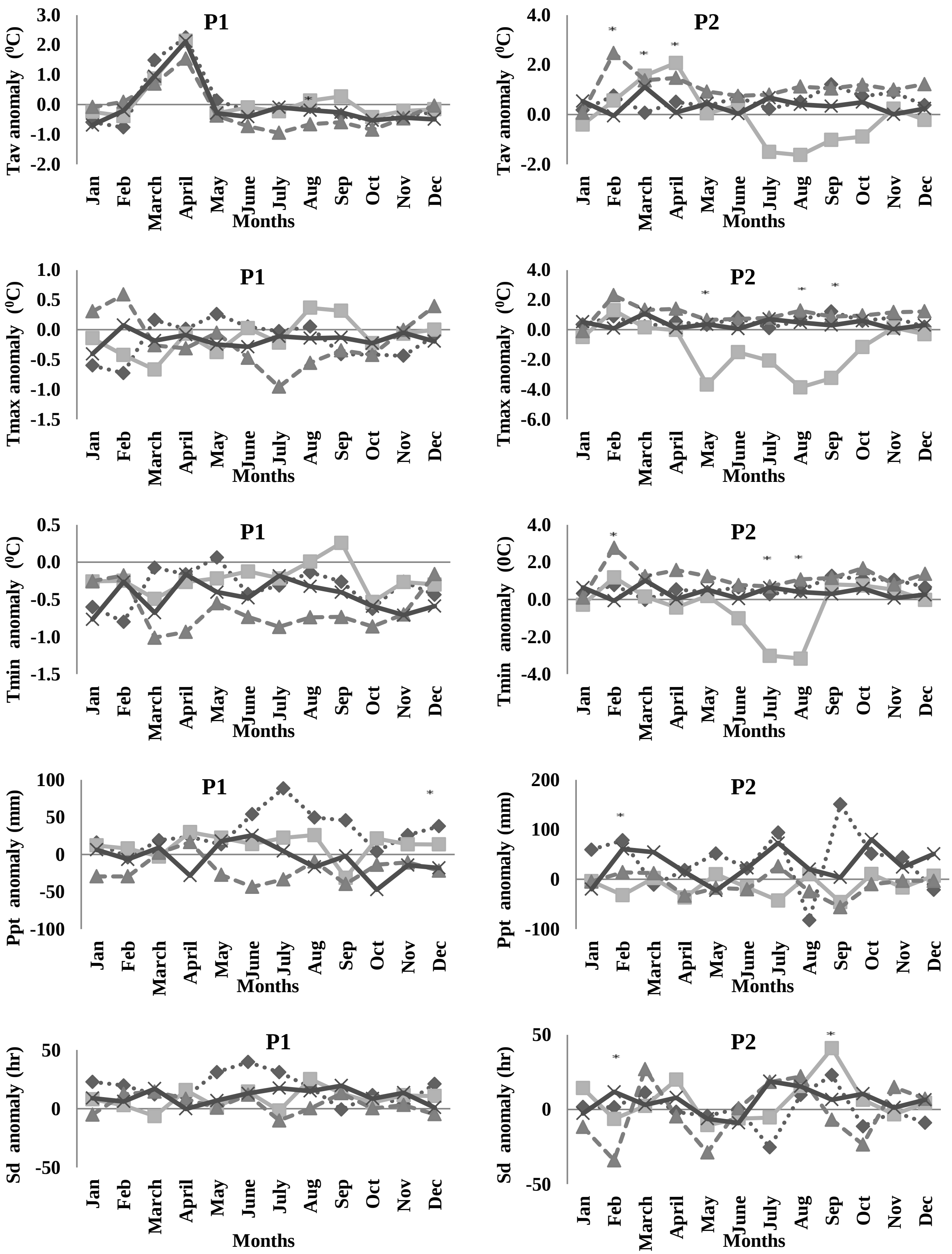


Fig. 2.2.7. Monthly climatic anomalies for different YG in PG7: Osaka, Wakayama. (P1 = period 1: = YG1, = YG2, = YG3, = YG4); (P2 = period 2: = YG5, = YG6, = YG7, = YG9). *indicates monthly variation is significant at 5% level.

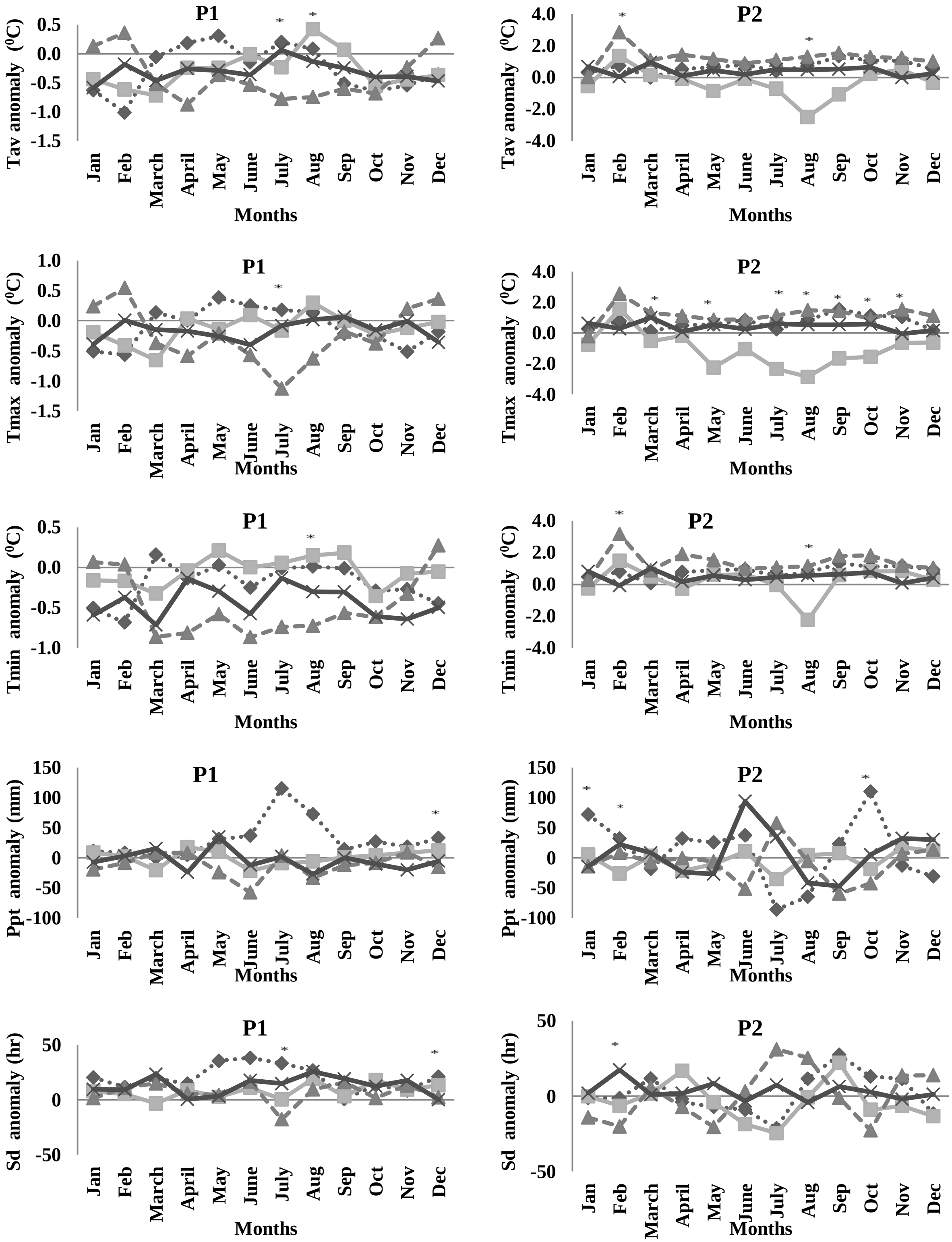


Fig. 2.2.8. Monthly climatic anomalies for different YG in PG8: **Nigata, Ehime, Shimane, Fukuoka, Saga, Nagasaki, Kumamoto, Oita, Miyazaki, Kagoshima. (P1 = period 1: = YG1, = YG2, = YG3, = YG4); (P2 = period 2: = YG5, = YG6, = YG7, = YG9).**

***indicates monthly variation is significant at 5% level.**

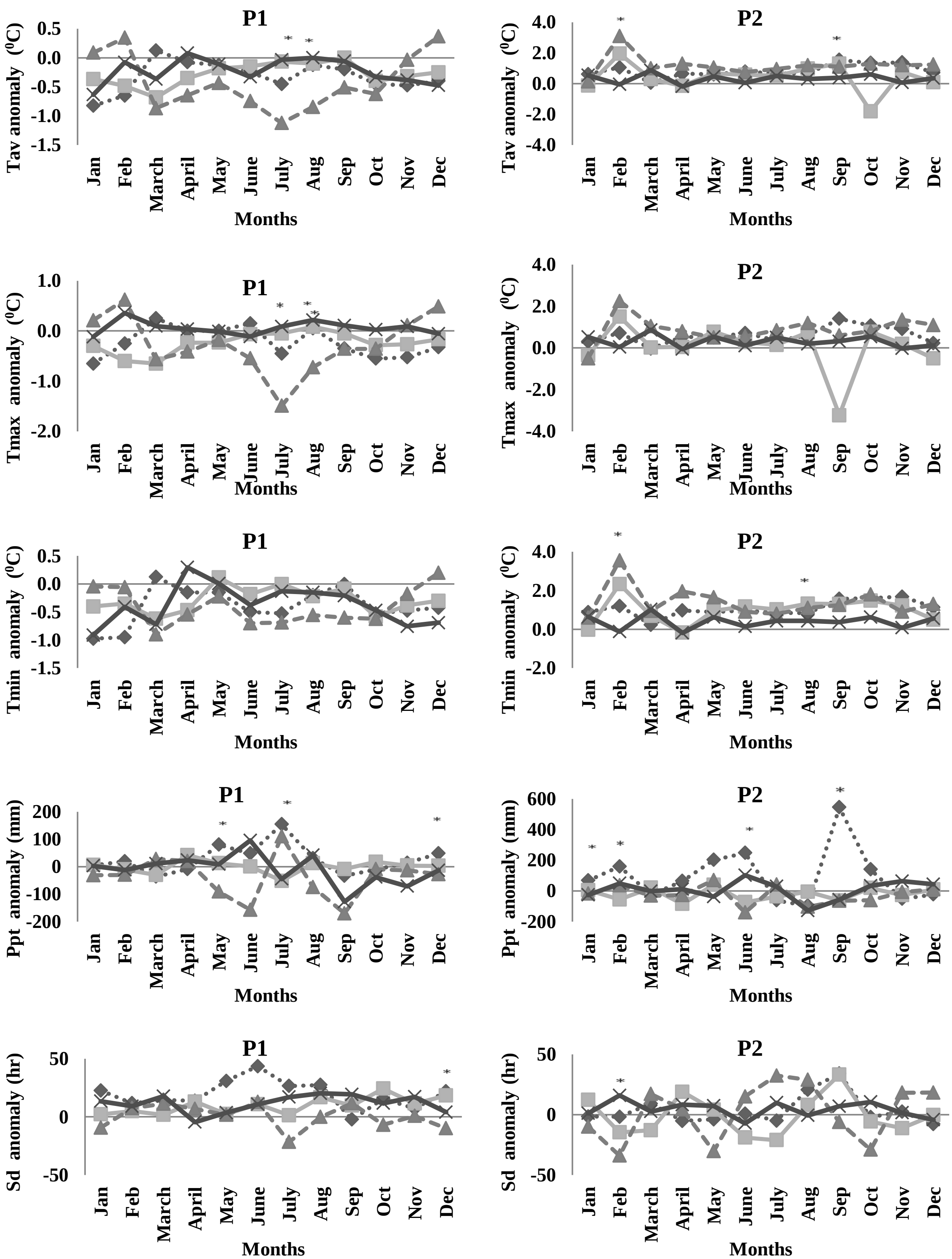


Fig. 2.2.9. Monthly climatic anomalies for different YG in PG9: Kochi. . (P1 = period 1: = YG1, = YG2, = YG3, = YG4); (P2 = period 2: = YG5, = YG6, = YG7, = YG9).

***indicates monthly variation is significant at 5% level.**

2.2.3.2. Relation between yield and climate parameter

Equations for two different periods of every PG depict which factor affects positively and which affects negatively and which climate factors are most imperative in determining yield variability for a particular region.

PG1

$YP1 = -0.188\ Sd_{JUL} + 0.188\ Sd_{JUN} + 0.226\ Tav_{AUG} - 0.177\ Ppt_{SEP} - 0.653\ Tmax_{SEP} + 0.850\ Tav_{SEP} - 0.351\ Tmin_{OCT}$ (1)

$YP2 = 0.266\ Sd_{OCT} + 0.297\ Tav_{AUG} - 0.333\ Tmin_{JUN} + 0.197\ Tav_{JUL} - 0.204\ Tmax_{AUG} + 0.187\ Tmax_{OCT}$ (2)

PG2

$YP1 = -0.261\ Ppt_{SEP} - 0.234\ Sd_{AUG} - 1.719\ Tmax_{SEP} + 3.462\ Tav_{SEP} - 1.942\ Tmin_{SEP} + 0.503\ Tav_{AUG} - 0.115\ Ppt_{OCT}$ (3)

$YP2 = 0.435\ Tmax_{AUG} - 0.251 Sd_{SEP} - 0.190\ Ppt_{JULY} - 0.498\ Tav_{JUN} + 0.378\ Tmin_{JUN}$ (4)

PG3

$YP1 = 0.330\ Sd_{AUG} + 0.295\ Sd_{JUN} + 0.404\ Tav_{OCT} - 0.325\ Ppt_{SEP} - 0.216\ Tav_{SEP}$ (5)

$YP2 = -0.438\ Ppt_{SEP} + 0.328\ Sd_{JUL} - 0.386\ Ppt_{JUN} + 0.331\ Sd_{OCT}$ (6)

PG4

$YP1 = -0.217\ Ppt_{JUL}$ (7)

PG5

$YP1 = -0.288\ Ppt_{OCT} + 0.212\ Tmax_{JUN} - 0.187\ Ppt_{JUL} - 0.214\ Ppt_{SEP} - 0.158\ Sd_{SEP}$ (8)

$YP2 = -0.266\ Ppt_{JUN} + 0.299\ Sd_{JUL} - 0.238\ Ppt_{SEP}$ (9)

PG6

$YP1 = 0.446\ Sd_{JUN} + 0.185\ Ppt_{JUN} - 0.216\ Tmin_{OCT} + 0.136\ Tmin_{AUG} - 0.199\ Ppt_{JUL} - 0.213\ Sd_{JUL} - 0.537\ Tmax_{JUN} + 0.670\ Tav_{JUN}$ (10)

$YP2 = -0.256\ Tmin_{OCT} + 0.281\ Sd_{JUL} - 0.264\ Ppt_{SEP} - 0.177\ Tmin_{SEP} + 0.148\ Sd_{OCT} + 0.122\ Tmax_{AUG}$ (11)

PG7

$YP1 = 0.216\ Ppt_{AUG}$ (12)

$YP2 = -0.349\ Tmin_{OCT} - 0.321\ Sd_{SEP} - 0.299\ Tmin_{JUN} - 0.266\ Sd_{AUG} - 0.271\ Ppt_{SEP}$ (13)

PG8

$YP1 = -0.210\ Sd_{SEP} + 1.078\ Tav_{JUN} - 0.258\ Ppt_{AUG} - 0.167\ Sd_{AUG} - 0.624\ Tmax_{JUN} - 0.143\ Ppt_{JUN} + 0.183\ Sd_{OCT} - 0.129\ Ppt_{JUL} - 0.349 Tmin_{JUN}$ (14)

$YP2 = 0.185\ Sd_{JUL} - 0.175\ Ppt_{SEP} - 0.138\ Ppt_{JUL}$ (15)

PG9

$YP1 = 0.437\ Tav_{AUG} - 0.295\ Ppt_{JUL} + 0.261\ Sd_{SEP}$ (16)

$YP2 = 0.740\ Tmin_{AUG} - 0.462\ Ppt_{JUN}$ (17)

From these analyses, it is clearly evident that relation between climate factors and yield changes from one period to another. Some factors which were most significant in earlier period is not that significant in recent years, while some new factors became more significant sometimes even with the same factor relationship changes in opposite direction. Differences in the two equations obtain in the same PG in the period 1 and period 2 can be explained by the relative change of climate factor in two periods:

In PG1, sunshine duration of June and July (Sd_{JUN}, Sd_{JUL}) along with average August temperature (Tav_{AUG}) were the most dominant factor in period 1 (Eq. 1) while sunshine duration in October (Sd_{OCT}), minimum temperature of June ($Tmin_{JUN}$) and average temperature of August (Tav_{AUG}) were for period 2. In both periods, average August temperature remains close to the standard in most YGs (Fig 2.2.1) and were the common factor influencing yield but other factors change. Sd_{JUN}, Sd_{JUL} were remarkably higher than standard in period 1which was not in period 2 and they were important factor in period1 but not in period 2. Similarly, Sd_{OCT} was important factor for period 2 as it showed smaller value (Fig 2.2.1) than period 1 indicating influence of higher day length in June, July and lower in October along with average August temperature are the important factor for PG1.

In PG2, September precipitation (Ppt_{SEP}) and maximum temperature ($Tmax_{SEP}$) along with August sunshine duration (Sd_{AUG}) were most important in period 1 whereas in period 2, August maximum temperature ($Tmax_{AUG}$), sunshine duration in September (Sd_{SEP}) and precipitation in July (Ppt_{JULY}) were most important. Consistently higher precipitation in most YGs was observed for September in period 1 than period 2 and July in period 2 than period 1 (Fig 2.2.2). Similarly, sunshine duration in August in period 1 was higher than period 2 and in September it was higher in period 2 than period 1.

In PG3, sunshine duration in August was relatively higher in most YGs in period 1 than 2 and was included in the equation for period 1 while September precipitation value did not change much between period 1 and period 2 and were included as significant factor for both periods.

In PG5, precipitation of October in period 2 was significantly lower in period 1 than period 2 (Fig 2.2.5) and precipitation of June was lower in period 2 than period 1and was included in the equation for period 2.

In PG6, higher sunlight duration and precipitation of June and July in period 1 than period 2 (Fig 2.2.6) made significant affect on yield (Eq. 10) and similarly September precipitation was higher in period 2 than period 1 (Fig 2.2.6) and was added in the equation for period 2. However, minimum temperature of October in both periods although differ relatively but were included in both equations since apparently soybean production in PG6 is very sensitive to minimum temperature of October.

In PG7, precipitation in August in period 1 was higher than period 2 which was the most important factor for period 1. Minimum temperature of October was very high in period 2 than period 1 was most significant factor for period 2.

In PG8, sunshine duration in September was consistently higher in all YGs in period 1compare to period 2 and August precipitation was higher in period 1 than period 2 and therefore they were included in the equation for period 1. In period 2, precipitation of September and July was important as they showed relatively higher fluctuation from the standard while in period 1 they were quite stable.

In PG9, average temperature of August was significantly lower in the period1 compare to period 2 and most important positive factor for period 1. Minimum temperature of August was significantly higher in period 2 compare to period 1 was included in the equation as most important factor. This indicates the relation between August temperature and yield did not change only minimum temperature became more important than average temperature in recent time (period 2). Thus changes in climate factor between 2 periods are responsible for changing the yield-climate relation between 2 periods for all the PGs.

These results imply that during the whole study period, precipitation and sunshine duration are probably the most influential factors determining soybean yield in Japan. In almost all locations excess precipitation is related to reduce yield, particularly for the month of September and July. Sunshine duration for the months of July, August and September are most crucial for yield. Average temperature seems to have minute effect on yield compare to precipitation except in some northern locations (PG1 and 2) where August and September average temperature positively affects the yield. Daily range of temperature (Tmax and Tmin) probably is more correlated with yield change than average temperature itself. In some northern PGs September Tmax and Tmin while in some southern PGs October Tmin showed negative association with yield.

2.2.4. Discussion

2.2.4.1. Climate change pattern between period 1 (1948-1989) and period 2 (1990-2012)

Our period wise climate changing pattern analysis for countrywide location (46 prefectures) provides another confirmation besides previous studies (Fujibe et al., 2007; Schaefer and Domroes, 2009) that average surface temperature is increasing. The trend of summer, winter and autumn average temperature increase is apparently higher in period 2 than period 1 in most PGs (Figs 2.2.1–2.2.9). This warming trend is comparatively higher in autumn than summer and winter. In fact, this difference is more than 1^0C in case of autumn average deviation and nearly 0.5^0C–0.8^0C in summer and winter months. Decreasing trend of summer precipitation accompanied by warmer temperature is quite evident in both periods (Figs 2.2.1–2.2.9) while at the same time autumn (particularly September) precipitation showed an increasing trend.

2.2.4.2. Precipitation pattern and yield

Our study links precipitation and daylight duration as the most important climate factors influencing yield affecting almost all location at different months of the growing season (Table 2.2.1). September precipitation followed by July precipitation perhaps is the most important factor that negatively affects yield in all regions. These 2 months corresponds to the near maturity (pod setting) and planting time of soybean production in Japan and excessive rainfall during this time lowers yield. A similar negative relation of precipitation during maturity was found in Argentina

Table 2.2.1. Summary for regression equations (1-17); (+) indicates positive influence and (-) indicates negative influence on yield. (PG1 = Hokkaido, Ibaraki, Tochigi, Gunma, Saitama, Chiva, Kanagawa, Nagano; PG2 = Aomori, Iwate, Akita, Yamagata, Shizoka, Tokushima, Nara; PG3 = Miyagi, Fukushima; PG4 = Tokyo, Yamanashi; PG5 = Gifu, Aichi, Mie, Shiga; PG6 = Hyogo, Tottori, Hiroshima, Yamaguchi, Toyama, Fukui, Ishikawa, Kyoto, Okayama, Kagawa; PG7 = Osaka, Wakayama; PG8 = Nigata, Ehime, Shimane, Fukuoka, Saga, Nagasaki, Kumamoto, Oita, Miyazaki, Kagoshima; PG9 = Kochi)

PG	PR	Ppt					Sd					Tav					Tmax					Tmin				
		JUN	JUL	AUG	SEP	OCT	JUN	JUL	AUG	SEP	OCT	JUN	JUL	AUG	SEP	OCT	JUN	JUL	AUG	SEP	OCT	JUN	JUL	AUG	SEP	OCT
PG1	P1				-		+	-						+	+					-						-
	P2										+		+	+					-		+	-				
PG2	P1				-	-			-					+	+					-					-	
	P2		-							-		-							+			+				
PG3	P1				-		+		+						-	+										
	P2				-			+			+															
PG4	P1		-																							
	P2																									
PG5	P1		-		-	-				-		+					+									
	P2	-			-				+																	
PG6	P1	+	-				+	-									-							+		-
	P2				-			+			+								+						-	-
PG7	P1			-																						
	P2				-				-	-												-				-
PG8	P1	-	-	-					-	-	-	+					-					-				
	P2		-		-			+																		
PG9	P1		-							+				+												
	P2	-																						+		

by Penalba et al., 2007 and positive relation with planting time and flowering was found in Brazil by Ferreira and Rao (2011), while in USA Thomson (1969) found no significant effect of excess rainfall during maturity. There is no significant changing pattern of September precipitation among the YGs in the periods except for some occasional YGs where it is much higher than standard. This indicates that the standard in precipitation pattern of September has been always a problem for soybean production in Japan. Only change in this aspect is the higher magnitude of precipitation from the period 1 to period 2 inflicting yield in a larger extent particularly for the southern regions (PG 6, 8). If this current trend continues yield trend in the southern PGs (5, 6, 8) will be significantly disrupted, which already can be seen in PG8 (Fig 2.2.8). Yield in northern regions (PG1, 2, 3) also affected by September precipitation particularly in the period 1. To some extent July precipitation also negatively affects yield in some regions (PG2, 3, 8). In general, decreasing trend is observed for July precipitation from period 1 to period 2 indicating that negative yield impact was more prominent in period 1 than period 2. Significant YG variability also exists in some regions (PG1, 4) for July precipitation making it an irregular or minor factor than September precipitation.

2.2.4.3. Sunshine duration pattern and yield

Sunshine duration is another important climate factor that affects yield. The association between yield and sunshine duration for most part of the growing season in general is positive. Summer and autumn sunshine duration (hr) has been decreased from period 1 to period 2. This decrease is greater in summer months than autumn months. July sunshine duration showed some significant variation between YGs in some locations (PG6, 8) in period 1. Similarly, in period 2 September sunshine duration showed some significant variation particularly in southern PGs (PG6). Association between sunshine duration and yield showed negative relation with summer and sometimes with autumn sunshine duration in some PGs (PG1, 2, 6). This effect of sunshine duration is highly correlated with the effect of increasing maximum temperature and precipitation which lowers yield and thus increasing sunshine duration is related with lowering yield.

2.2.4.4. Temperature pattern and yield

Regression analysis (Table 2.2.1) reveals that average August and September temperature had positive association with soybean yield particularly for northern regions. Similar positive relation between summer temperatures and yield (July-August) was found for northern regions especially for Hokkaido in a previous study by Iwakiri (1976). Similar positive effect of increasing average temperature has been reported in China for maize and wheat (Liu et al., 2010; Xiao et al., 2008; Yang et al., 2007). Climate anomalies (Figs 2.2.1–2.2.9) showed average August average temperature had consistent significant variation in period 1and period 2 for most regions. Until now the increasing trend of average August temperature seems to have positive impact in the northern regions (PG1, 2, 3). In the southern regions yield seems to be unaffected by the average temperature changing pattern but affected by the daily range of temperature variability of June, August, September, and October (Tmax and Tmin). Night temperature of June and October (Tmin) and Day temperature (Tmax) of June and September showed negative relation in northern and southern PGs. Similar negative relation with summer day time temperature was also found by Ferreira and Rao (2011) but positive relation between night temperature during early growing period was reported by Penalba et al. (2007) which is contradictory to our observation.

On the basis of this yield and climate changing pattern analysis it can be suggested that there is a regional pattern in the relation between soybean yield and climate factors and the relationship is not constant over time rather variable and this extent of variation depends on the extent of climate change. Lastly, it can be concluded that classification of prefecture groups and year groups was necessary to derive the quantitative yield climate relation and this classification provides a very important basis for developing any statistical soybean climate response model for Japan,

Chapter 3

Influence of climate factors on soybean yield in Asia

3.1. Validation of solar radiation estimation model based on daily range of temperature

3.1.1 Introduction

Solar radiation (R_s; MJ $m^{-2}d^{-1}$) is a driving factor in all physical and biochemical processes on the earth's surface. Crop production also depends fundamentally on the amount of intercepted R_s. Despite its significance, there are few weather stations around the world that collect R_s data due to the cost, maintenance and calibration requirements (Ball et al., 2004; Liu et al., 2009). Even where R_s data have been routinely measured, there are often significant gaps as a result of instrument errors or failures. Moreover, historical data are strongly recommended to evaluate the effects of climatic change on crop production, and these data typically lack R_s information. Hence, empirical models estimating R_s from commonly available climate data have been required.

One common approach to predicting R_s is the product of extraterrestrial radiation (R_a; MJ $m^{-2}d^{-1}$) and an estimated atmospheric transmissivity coefficient (T_t) as follows:

$$R_s = R_a \times T_t \qquad (1)$$

Different approaches for determining T_t have been used in different models. Some models are based on temperature differentials (Hargreaves and Samani, 1982; Bristow and Campbell, 1984), cloudiness, or daily sunshine hours (Angstrom, 1924). Although the basis of daily sunshine hours produces a relatively reliable estimation (Centeno 1991; Homma et al., 2007), the number of observations is still limited in the world. Another widely used model is the Hargreaves and Samani (1982) model in which T_t is estimated from the difference between daily maximum temperature (T_{max}, °C) and minimum temperature (T_{min}, °C) as follows:

$T_t = K_{Rs} (T_{max} - T_{min})^{0.5}$ (2)

This model is based on the assumption that the difference between daily maximum and minimum temperatures provides a general indication of cloudiness. Compared to clear skies, cloud cover usually decreases the maximum air temperature due to lower solar radiation levels and increases minimum air temperature due to increased downward emission and reflection of long wave radiation by clouds at night (Allen 1997). Although other important factors, e.g., wind speed, humidity, elevation, precipitation and available soil water for evaporation, also affect transmissivity, these factors are not included in the model by assuming that the effects are fairly constant over a period of as long as one month (Hargreaves and Samani, 1982). Accordingly, the model is commonly applied to estimate monthly R_s based on weekly or monthly averages of daily temperature ranges (Meza and Varas, 2000; Samani, 2000). Despite the inaccuracy caused by the assumption, the advantage in estimating R_s using the model is greater because temperature data are available for wider areas and over longer periods around the world (Homma et al., 2007; JMA, 2013; GHCN, 2013).

Annandale et al. (2002) set K_{Rs}, an empirical coefficient in the model, to 0.16 for inland sites and 0.19 for coastal sites. However, Ball et al. (2004) and Fletcher and Moot (2007) reported that model performance is improved when the K_{Rs} value is not fixed (0.16 or 0.19) and is instead calibrated to each site. Not only location differences but also seasonal differences in K_{Rs} are quite important when using the model for the estimation of R_s to evaluate effects of climate on crop production because seasonal patterns of R_s have a significant meaning in crop production. Historical changes in K_{Rs} are also quite important when the evaluation is conducted using historical data. This study aimed to evaluate seasonal and historical changes in K_{Rs} and their effects on the estimation of R_s. The effects on the estimation of R_s were evaluated by setting K_{Rs} as a constant. We used daily weather data because daily values are recommended when analyzing the effects of climate on crop production. Moreover, the dataset in Japan was selected because the dataset included R_s and its quality was certified by a certain standard (JMA, 2012).

3.1.2. Materials and methods

3.1.2.1. Database and data sources

10 different locations were selected which are representative agricultural areas and widely distributed in Japan (Fig. 3.1.1). The daily maximum temperature (T_{max}), minimum temperature (T_{min}) and solar radiation (R_s) data over the periods of 1981-1985 and 2003-2007 were collected from the Japan Meteorological Agency (JMA, 2012). Extraterrestrial radiation (R_a) was calculated using standard geometric methods for any given day of the year (DOY) based on latitude, solar constant, sunset hour angle and solar declination angle. The dataset was used for the estimation of K_{Rs} and model validation.

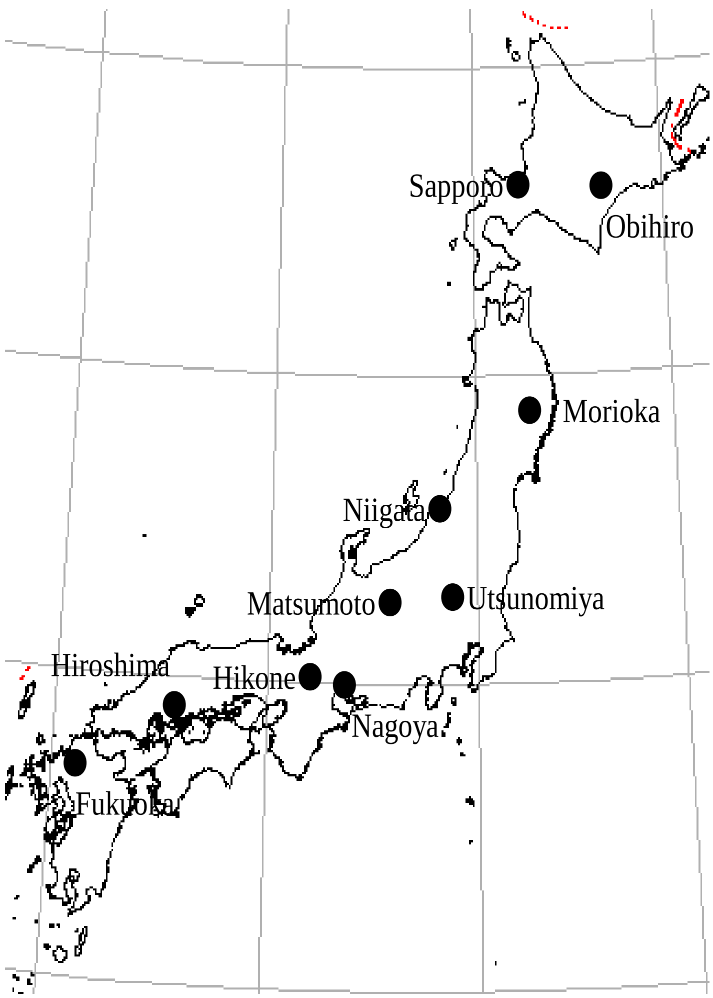


Fig. 3.1.1. Map of locations analyzed in this study.

3.1.2.2. Estimation of K_{Rs}

The transmissivity coefficient (T_t) was estimated using the following equation:

$T_t = K_{Rs} \times (1 + 2.7 \times 10^{-5} \times A_{lt}) \{(T_{max} - T_{min})^{0.5}\}$ (3)

The equation was modified by Annandale et al. (2002) to include a correction factor for altitude (A_{lt}; m). By combining Equation (1) and (3), Rs is expressed as follows:

$R_s = K_{Rs} [R_a (1 + 2.7 \times 10^{-5} \times A_{lt}) \{(T_{max} - T_{min})^{0.5}\}]$ (4)

Depending on the equation, K_{Rs} was obtained as a regression coefficient where $[R_a (1 + 2.7 \times 10^{-5} \times A_{lt}) \{(T_{max} - T_{min})^{0.5}\}]$ is an independent variable and R_s is a dependent variable with the intercept equal to zero (as shown in Fig. 2). The K_{Rs} value for each month and each prefecture was estimated. Differences in K_{Rs} between the periods of 1981-1985 and 2003-2007 as well as for each month were tested using two-way ANOVA.

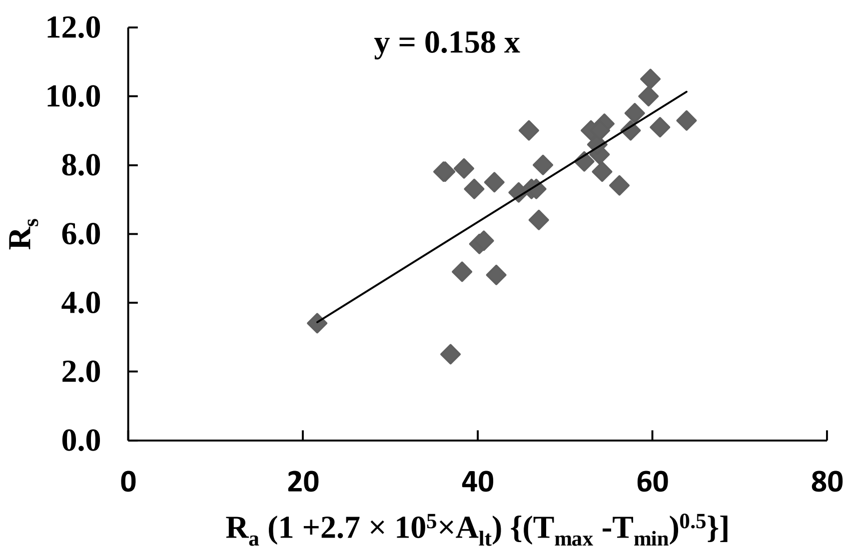


Fig. 3.1.2. Relation between independent and dependent variables in Equation 4. Data from January 1981 at Obihiro are used. An empirical constant (K_{Rs}) in the equation is estimated as the slope of the regression line with the intercept equal to 0 (0.158 in this example).

3.1.2.3. Model testing and assessment

To evaluate the effect of differences in K_{Rs} on Rs prediction, daily R_s was estimated using Eq. 3 with K_{Rs} = 0.16 and compared with the observed R_s. Bias and root-mean-square error (RMSE) were used as measures of the estimated R_s accuracy as follows:

$$\text{Bias} = \Sigma\ (\text{estimated } R_s - \text{measured } R_s) / n, \quad (5)$$

$$\text{RMSE} = (\Sigma\ (\text{estimated } R_s - \text{measured } R_s)^2 / n)^{0.5} \quad (6)$$

Bias shows the over- or under-estimation, and RMSE shows the magnitude of error. Two-way ANOVA was also conducted to quantify the bias and RMSE.

3.1.3. Results

3.1.3.1. Effect of locations, periods and seasons on K_{Rs}

The K_{Rs} coefficient varied from 0.148 (Utsunomiya) to 0.166 (Sapporo and Fukuoka) during the entire study period (1981-2007; Table 3.1.1.). The values generally decreased with the distance from sea, except Niigata (Table 3.1.1 and Fig. 3.1.3). In almost all locations, except Hikone and

Table 3.1.1. Comparison of location-wise K_{Rs} variation for 1981-1985 and 2003-2007.

Location	Year	Obihiro	Sapporo	Morioka	Utsunomiya	Niigata	Matsumoto	Nagoya	Hikone	Hiroshima	Fukuoka
Latitude		42.92N	43.06N	39.7N	36.55N	37.91N	36.25N	35.17N	35.28N	34.4N	33.58N
Longitude		143.21E	141.33E	141.17E	139.87E	139.05E	137.97E	136.97E	136.24E	132.46E	130.38E
Altitude		38.4 m	17.2 m	155.2 m	119.4 m	1.9 m	610 m	51.1 m	87.3 m	3.6 m	2.5 m
Distance from sea		45 km	14 km	69 km	67 km	2 km	81 km	19 km	46 km	6 km	2 km
K_{Rs}	1981-1985	0.151	0.163	0.146	0.144	0.147	0.151	0.154	0.161	0.162	0.162
	2003-2007	0.160	0.170	0.151	0.152	0.157	0.156	0.165	0.160	0.165	0.171
	Whole	0.155	0.166	0.149	0.148	0.152	0.153	0.160	0.161	0.163	0.166
ANOVA	Period (P)	<0.01	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	0.73	0.05	<0.01
	Month (M)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	P x M	0.71	0.55	0.47	<0.01	0.26	0.52	0.74	0.31	0.29	0.20

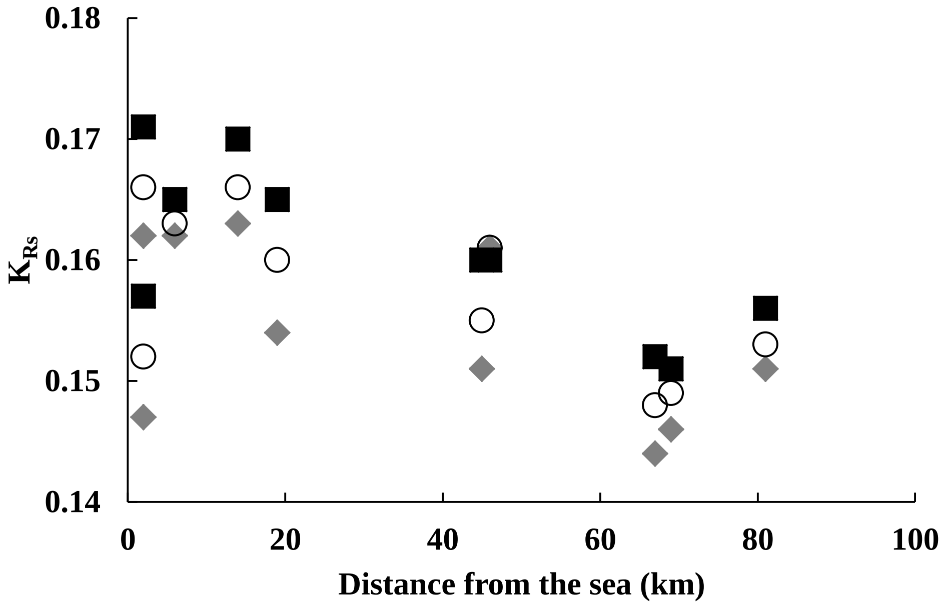


Fig. 3.1.3. Relation between K_{Rs} and distance from the sea. K_{Rs} was obtained for 1981 – 1985 (◆), 2003 – 2007 (■) and whole (○) periods.

Hiroshima, K_{Rs} significantly increased from the 1981-1985 period to the 2003-2007 period (note: the probability of period effect in Hiroshima was 0.051). Changes in the daily temperature range (T_{max} –T_{min}) and solar radiation (R_s) can help explain the difference in K_{Rs} values between periods. Equation (4) indicates that R_s is proportional to T_{max} – T_{min}. However, R_s tended to increase from 1981-1985 to 2003-2007, but T_{max} – T_{min} tended to decrease (Table 3.1.2). The K_{Rs} value also showed significant (at 1% level) monthly variations. Six out of 10 locations, namely Obihiro, Sapporo, Morioka, Utsunomiya, Matsumoto and Nagoya, showed a similar pattern of high K_{Rs} values (0.17 to 0.19) between the months of January and March followed by a steep decline between May and July (0.12 to 0.14) and a gradual increase from August to December (Fig. 3.1.4). However, Nigata showed an opposite pattern of K_{Rs} values, i.e., higher values in the middle of the year and lower values in the late and early months of the year. The K_{Rs} values for Hikone, Hiroshima and Fukuoka did not show clear patterns for any given year. These patterns remained almost unchanged for both time periods (1981-1985 and 2003-2007) because the period and month interactions for K_{Rs} values were not significant, except in Utsunomiya (Table 3.1.1).

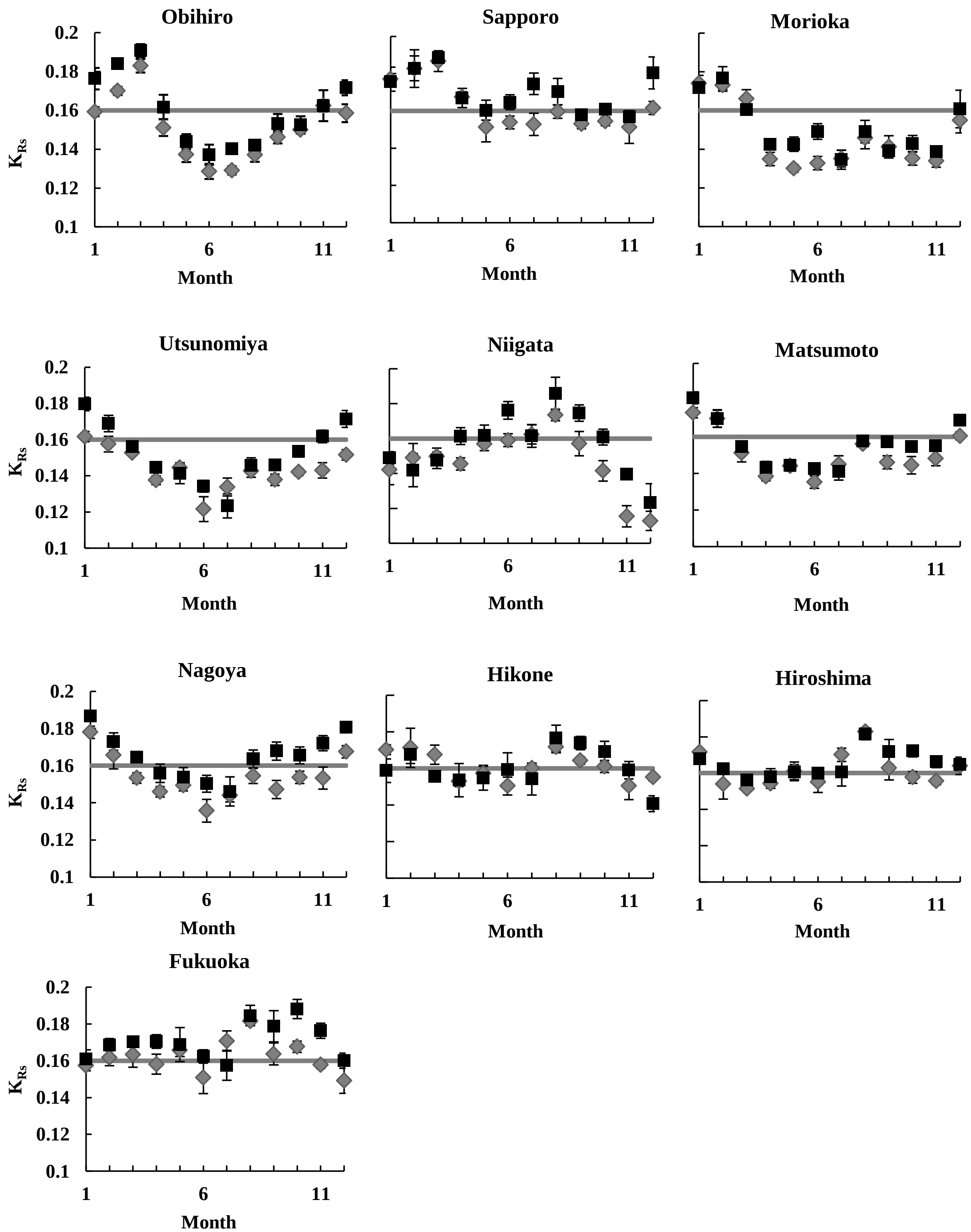


Fig. 3.1.4. Monthly variation of K_{Rs} at different locations for the 1981-85 (◆) and 2003-2007 (■) periods.

Table 3.1.2. Comparison of location-wise daily range of temperature ($T_{max} – T_{min}$, °C) and R_s (MJ m^{-2} d^{-1}) variation for 1981-1985 and 2003-2007.

Location	Year	Obihiro	Sapporo	Morioka	Utsunomiya	Niigata	Matsumoto	Nagoya	Hikone	Hiroshima	Fukuoka
T_{max} - T_{min}	1981-1985	10.65	7.86	9.31	10.08	6.85	11.07	8.72	7.73	7.86	7.44
	2003-2007	10.45	7.50	8.86	9.59	7.03	11.21	8.73	7.56	8.50	7.25
	Whole	10.55	7.68	9.09	9.84	6.94	11.14	8.72	7.64	8.18	7.34
ANOVA	Period (P)	0.34	<0.01	<0.01	<0.01	0.11	0.48	0.90	0.16	<0.01	0.08
	Month (M)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	P x M	0.52	0.65	0.77	<0.01	0.02	0.13	0.02	0.14	0.86	0.61
R_s	1981-1985	12.52	12.18	12.03	12.45	11.39	14.46	12.84	13.00	13.00	13.16
	2003-2007	13.17	12.52	12.27	12.89	12.24	15.09	13.83	12.97	12.97	13.71
	Whole	12.84	12.35	12.15	12.67	11.81	14.77	13.33	12.98	12.98	13.43
ANOVA	Period (P)	<0.01	0.12	0.34	0.13	<0.01	0.01	<0.01	0.91	0.91	<0.05
	Month (M)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	P x M	0.37	0.38	0.28	0.39	0.52	0.57	0.40	0.33	0.78	0.33

3.1.3.2. Errors in R_s estimation with a constant K_{Rs} value

A constant value of K_{Rs} (= 0.16) produced bias in the R_s estimation for both periods in a pattern that was somewhat similar but inverse to the monthly variation pattern of K_{Rs} (Fig. 3.1.5). Bias for the entire period was the highest in Utsunomiya (1.72 MJ m^{-2}) and the lowest in Fukuoka (–0.35 MJ m^{-2}; Table 3.1.3). The bias significantly changed towards negative from 1981-1985 to 2003-2007, except in Hikone, where K_{Rs} was similar between the periods. The difference between the periods was the largest in Nagoya (1.14 – 0.20 = 0.94 MJ m^{-2}) and the smallest in Hikone (0.29 – (0.15) = 0.14 MJ m^{-2}). ANOVA showed that the interaction of period and month did not significantly contribute to bias (Table 3.1.3), except at Morioka.

RMSE changed in conjunction with extraterrestrial radiation (R_a), with a maximum around June (Fig. 3.1.5). Moreover, RMSE tended to increase from 1981-1985 to 2003-2007, except in

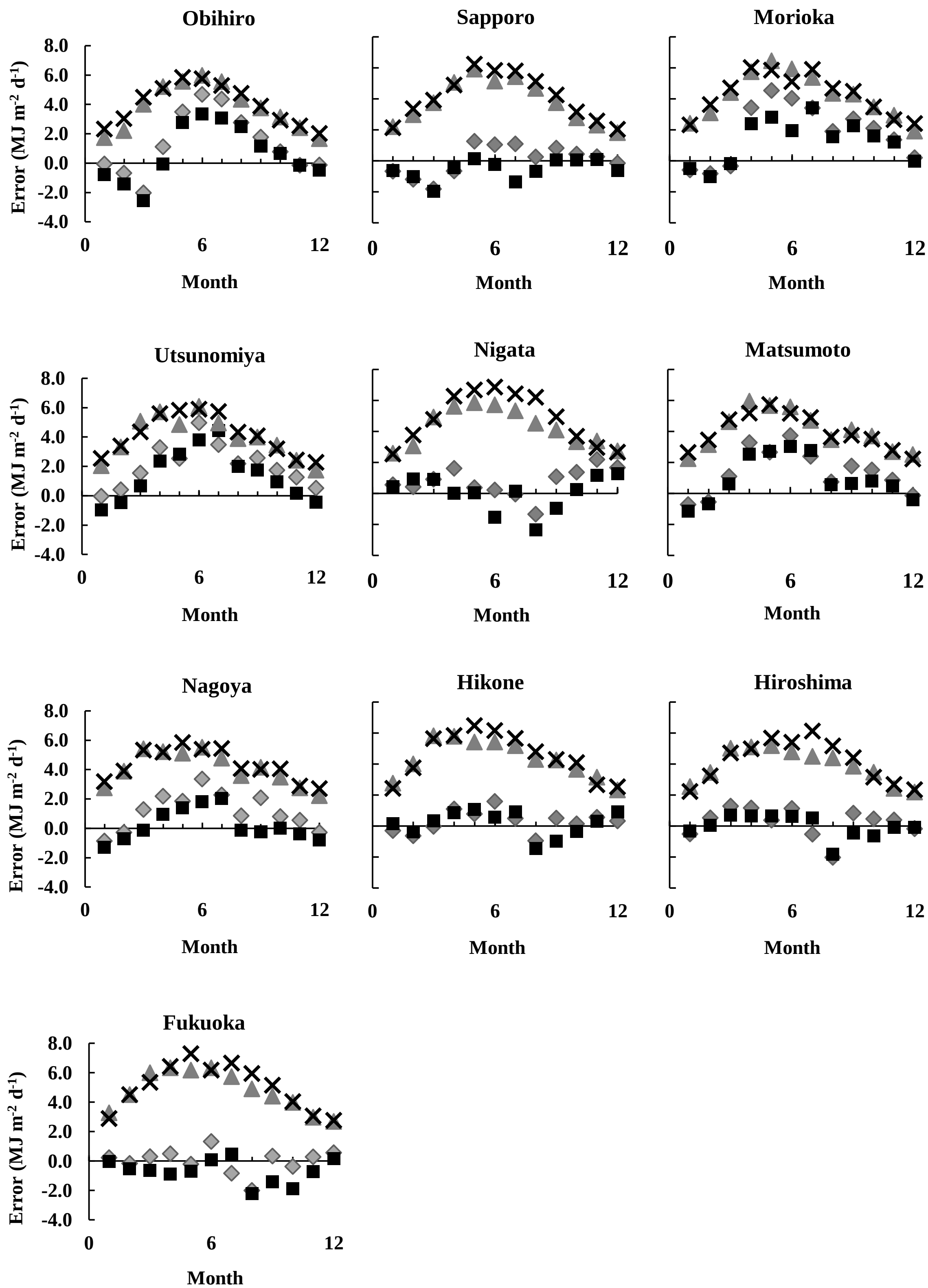


Fig. 3.1.5. Monthly variation of bias between the 1981-1985 (◆) and 2003-2007 (■) periods and RMSE for the 1981-1985 (▲) and 2003-2007 (×) periods in different locations.

Table 3.1.3. Comparison of location-wise variation in bias (MJ m^{-2} d^{-1}) and RMSE (MJ m^{-2} d^{-1}) for 1981-1985 and 2003-2007. Solar radiation was estimated by setting K_{Rs} = 0.16.

Location	Year	Obihiro	Sapporo	Morioka	Utsunomiya	Niigata	Matsumoto	Nagoya	Hikone	Hiroshima	Fukuoka
Bias	1981-1985	1.32	0.05	1.82	2.03	0.74	1.38	1.14	0.29	0.23	-0.01
	2003-2007	0.66	-0.56	1.29	1.41	0.02	0.98	0.20	0.15	-0.03	-0.69
	Whole	0.99	-0.25	1.55	1.72	0.38	1.18	0.67	0.22	0.10	-0.35
ANOVA	Period (P)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.54	<0.01	<0.01
	Month (M)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	P x M	0.61	0.14	0.04	0.17	0.15	0.79	0.51	0.69	0.35	0.27
RMSE	1981-1985	3.79	3.81	4.20	3.95	4.26	4.03	4.06	4.33	3.90	4.77
	2003-2007	3.98	4.11	4.26	4.12	4.81	3.97	4.32	4.52	4.16	5.01
	Whole	3.89	3.96	4.23	4.04	4.53	4.00	4.19	4.42	4.03	4.89
ANOVA	Period (P)	<0.05	<0.01	0.54	0.18	<0.01	0.59	<0.05	0.09	<0.05	<0.05
	Month (M)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
	P x M	0.21	0.94	0.17	0.33	<0.01	0.64	0.57	0.13	0.00	0.01

Matsumoto, and had a significant difference in 6 out of 10 locations. A significant interaction between period and month for RMSE was observed in Niigata, Hiroshima and Fukuoka.

Although the estimated R_s better corresponded with the measured R_s in Obihiro where RMSE was the lowest, the model with K_{Rs} = 0.16 tended to overestimate when the measured R_s was low, and the model tended to underestimate when the measured R_s was high (Fig.3.1.6). The relation between measured and estimated R_s also had a seasonal variation, i.e., the model tended to overestimate from April to July in comparison with the estimation from November to March.

3.1.4. Discussion

Solar radiation (R_s) is one of the major determinant factors of crop production, but the observations have locational and historical limitations (WRDC, 2013). Accordingly, the

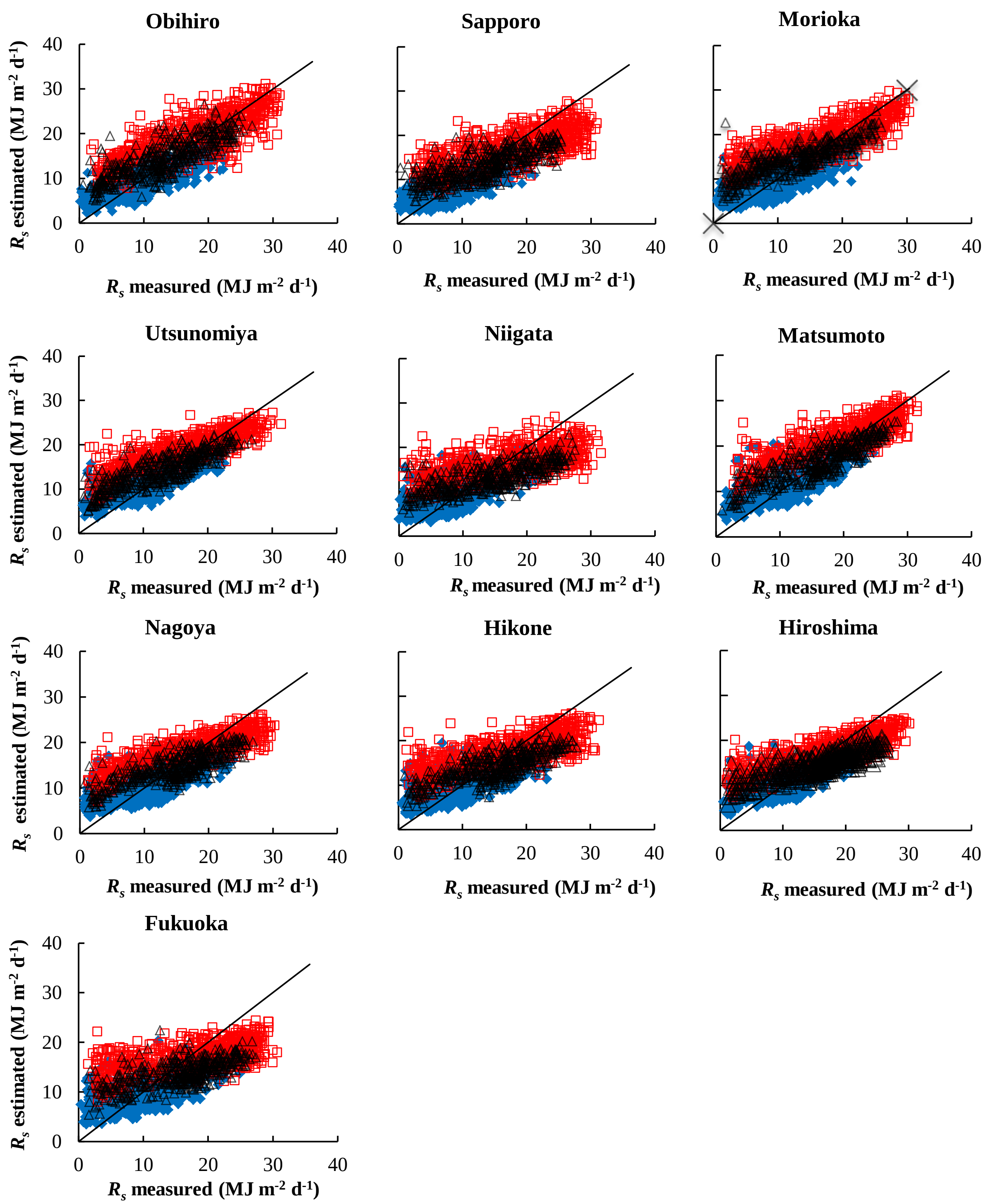


Fig. 3.1.6. Relation between estimated and measured R_s for November-March (◆), April-July (□) and August-September (△) for 2003 to 2007.Solar radiation was estimated by setting K_{Rs} = 0.16.

estimation of R_s is quite important when the relation between weather and crop production is historically analyzed in a wide range of locations. Among many methods to estimate R_s, models based on sunshine hours are most reliable (Angstrom, 1924; Kondo et al., 1991; Centeno, 1991). However, sunshine hours have the same problem as R_s in terms of data availability (Homma et al., 2007). This study focused on the estimation method based on temperature, which is historically collected in a large number of locations (JMA, 2013; NOAA, 2013).

The Hargreaves and Samani (1982) model has been tested and accepted as a reasonable method for estimating solar radiation by several previous studies (Ball et al., 2004; Fortin et al., 2008; Bandyopadhyay et al., 2008) for a wide range of locations. Some studies have modified the original model by adding one more coefficient (De Jong and Stewart, 1993; Hunt et al., 1998; Chen et al., 2004), which commonly produces better results but only for a specific location because the goals did not encompass the examination of diverse locations (Liu and Scott, 2001). In fact, Liu et al. (2009) showed that the original Hargreaves and Samani (1982) model (with or without the Annandale et al., 2002 modification) is still more accurate than the complex modified model for a wide range of locations. Although an alternate method, which estimates R_s based on temperature, has also been proposed (Bristow and Campbell, 1984 and modified by Weiss et al. (2001), Ball et al. (2004) concluded that the Hargreaves and Samani (1982) model with the Annandale et al. (2002) modifications is better than the Bristow and Campbell (1984) model modified by Weiss et al. (2001). We selected the model according to Ball et al. (2004).

Because dry matter production is primarily dependent on the accumulation of intercepted R_s, bias in the R_s estimation is more important than RMSE. To characterize the bias variability, we first calculated the empirical constant (K_{Rs}) in the model. The recommended values by Annandale et al. (2002) for K_{Rs} are 0.16 for inland sites and 0.19 for coastal sites. The K_{Rs} estimated in this study also tended to decrease along with the distance from the sea (Fig. 3.1.3). To estimate K_{Rs} more accurately, other weather factors, such as humidity and precipitation, might be necessary (Thornton and Steven, 1999). However, such modification requires other weather data and decreases the applicability of the model. In this study, we did not modify the model, and we set K_{Rs} to 0.16 to estimate R_S because K_{Rs} was approximately 0.16 .The difference in K_{Rs} between the constant (0.16) and actual values produced bias. Accordingly, the average K_{Rs} ranged from

0.166 at Fukuoka to 0.148 at Utsunomiya, which corresponded to the average bias ranging from –0.35 MJ m^{-2} at Fukuoka to 1.72 at Utsunomiya.

The analysis in this study also revealed that K_{Rs} has a distinct seasonal pattern in most areas studied (Fig.3.1.4) and that the difference of the seasonal pattern against K_{Rs} = 0.16 created seasonal bias differences (Fig 3.1.5). In this study, most locations tended to have a lower K_{Rs} and higher bias in the summer, but Niigata had a higher K_{Rs} and lower bias in the summer. The difference in monthly bias between the largest and smallest was largest at Obihiro (6.3 MJ m^{-2}) and smallest at Hikone (2.3 MJ m^{-2}). Abraha and Savage (2008) also reported that the Hargreaves et al. (1985) model, which was originally referred from the Hargreaves and Samani (1982) model, tends to overestimate in the summer. Apart from the seasonal pattern, K_{Rs} also changed with period (Fig.3.1.4). Therefore, reproducing long-term historical data of R_s can yield different accuracy levels over the studied period. Weather data indicated that this periodic increase in K_{Rs} was caused not only by increased solar radiation but also by decreased daily temperature range (because K_{Rs} is proportional to R_s divided by $T_{max} – T_{min}$). Several studies have indicated that the global warming trend commonly decreases the daily range of temperature because the increase in daily minimum temperature is commonly larger than that of daily maximum temperature (Karl et al, 1991; Kawatsu et al., 2007). Urbanization also decreases the daily range of temperature (Suzuki et al., 2001). Although historical changes in solar radiation are not obvious (Pinker et al., 2005; Wild et al., 2007), the decreasing trend in the daily range of temperature itself produces an increasing trend in K_{Rs}. The interaction between month and period was small for K_{Rs}, thereby suggesting that the seasonal pattern of K_{Rs} is location specific and less affected by global warming.

RMSE showed a more distinct seasonal pattern than bias (Fig 3.1.5). The pattern showed the maximum around June and the minimum around December, which correspond with the extraterrestrial radiation (R_a). This feature was also revealed in Fig. 3.1.6. which indicates that the relation between measured and estimated R_s was more widely distributed from April to July than from August to March. The wider distribution was obvious, especially in the overestimation area in the figure, which was one of the causes of larger bias. Bias tended to change towards negative, and RMSE tended to increase over the decades. The increase in RMSE was mainly due to increased RMSE from April to September (Fig 3.1.5).

The results in this study suggested that the estimation of R_s using the Hargreaves and Samani (1982) model has a considerable problem with bias when analyzing crop production, i.e., bias changes depending on the location, year and, especially, month. However, using the model may remain the best method for the present situation in which obtaining adequate and qualified data for R_s around the world is quite difficult, especially in developing countries (Thornton and Running, 1999; Homma et al., 2007; Liu et al., 2009). Accordingly, the difference in bias must be considered when the estimation of R_s by the model is applied to analyze crop productivity. For example, the maximum location-wise difference in bias was 2 (MJ m^{-2}) in this study corresponding approximately to 15% of R_s. The maximum periodic difference was 1 (MJ m^{-2}) corresponding to 7%, and the maximum monthly difference was 6.5 (MJ m^{-2}) corresponding to 50%. These values may suggest that the method is not suitable to discuss seasonal changes in productivity. The relatively smaller periodic difference together with the smaller interaction between period and month for bias (Table 3.1.3) suggest that the evaluation of seasonal pattern of K_{Rs} in the present situation greatly improved the estimation accuracy of R_s for the past decades. Recently, satellite-based R_s measurements have been tested (Pinker et al., 2005; Lu et al., 2011). Although the method still requires calibration around the globe, evaluation of the seasonal pattern of K_{Rs} using satellite-based R_s may be advantageous.

3.2 Soybean production in Asia in relation with climate factors

3.2.1. Introduction

Soybean is originated from Asia. The first historical reference of soybean was found in China from records of 664 B.C (Ho 1974) and it was first domesticated in the eastern half of north China in about the 11^{th} century B.C. (Hymowitz, 1970). Historically it was used as a medicinal plant in ancient China. Since then its use has been widely diversified and consumption of soybeans and soybean products has risen rapidly. With increasing population its demand is expected to increase even more rapidly in future for example, world per capita use of vegetable oils is projected to rise 15 percent by 2021 and major source is expected to be soybean (USDA, 2012). Therefore increasing production is a prime concern in this decade.

Asia, the largest continent in the world with a grand total of 1,633,521,000 ha cultivation area of which only 1.2 % (19,956,807 ha) is used for soybean cultivation with a total production of 29,559,505 tonnes in 2011 (FAOSTAT, 2014). Still this production is not enough to meet the regional demand and many countries like China and Japan have to import soybean goods from North (USA) and south (Brazil) American countries. Soybean production and yield is highest in North and South American countries. Apart from the cultivation area difference there is also vast yield difference between American and Asian countries. Average yield for 2011 in Asia was 1.5 t/ha whereas in North America it was 2.8 t/ha which is almost double (FAOSTAT, 2014). Under such circumstances to identify the factors that cause this yield variation has been the focus point of study among agronomist. Among the various factors climate is one of the important issue influencing yield apart from management practice and genotypic variation and historical basis of yield change can be helpful for future improvement in yield potential (Ainsworth et al., 2011).

Soybean can grow in a wide range of climate from cool temperate zone to warm tropics. However, growth performance and yield is presumably different under different climate condition. Moreover, concurrent trend of climate change and global warming expected to decrease global crop production particularly in the lower latitude areas and increase in upper latitude areas (Easterling et al., 2007; Battisti and Naylor, 2009) and their impact on soybean production is another controversial topic as accurate yield change prediction is relatively difficult for soybean than other crops (Izumi et al., 2013) because of its regional differential response to temperature (Zhang and Huang 2012; Hatfield et al., 2011). For this purpose regional level study is needed to form a statistically and agronomically sound crop-climate relation based on historical trend. In this study we intend to investigate the yield difference among different countries in Asia in respect with countries of North (USA) and South (Brazil) America. We also investigate the influence of climate factors of those countries to draw inference about the yield difference especially relying on the historical trend of yield and climate relation. Another purpose of the study was to confirm the impact of global warming for soybean yield in Asia.

3.2.2. Materials and methods

3.2.2. 1. Study region

Soybean crop is grown in wide range of locations from 45^0 N to 7^0 S latitude and 141^0 E to32^0 E longitude in Asia. Almost 27 countries in Asia cultivated soybean in 2012 to some extent but the total harvested area and production quantity were highly variable among the countries (FAOSTAT, 2014). 11 countries from Asia were selected based on their gross contribution to the total production in recent years based on FAO statistics (2012) data; and 2 other leading countries in soybean production, USA and Brazil to compare with varied locations for our study. Therefore in total 13 countries were selected; USA, Brazil, Turkey, Kazakhstan, China, South Korea, North Korea, Japan, India, Myanmar, Indonesia, Thailand, and Viet Nam (Fig 3.2.1). Most of these countries have been growing soybean since 1960 and soybean is a common crop in their cropping pattern.

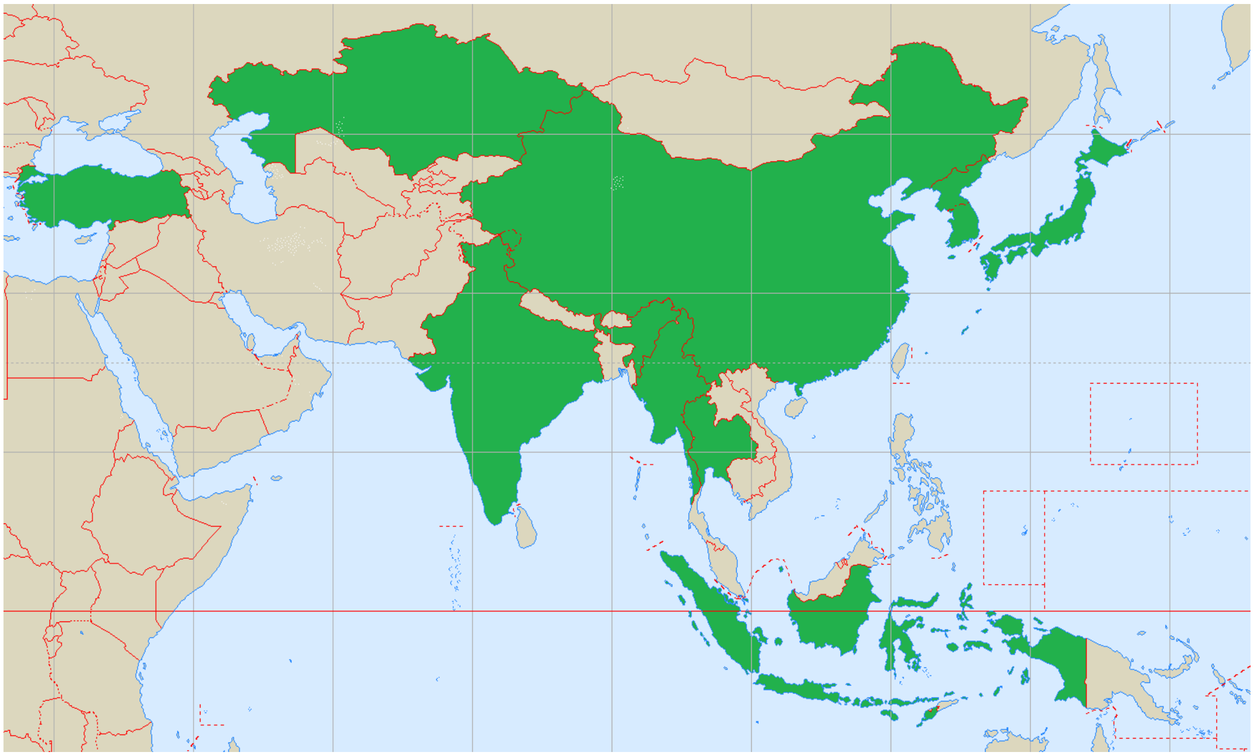


Fig. 3.2.1. Map of Asia showing the study region.

3.2.2. 2. Data collection

The study was based on yield and climate statistics in country level over 27 year time period from 1982 to 2008. Soybean harvested area, production and yield data were collected from 1982 to 2008 from the crop production database of the Food and Agriculture Organization of the United Nations (FAO; http: //faostat.fao. org) for 13 countries in order to form yield database. 5-4 weather stations were selected to get monthly climate data such as monthly average temperature (Tav), monthly maximum temperature (Tmax), monthly minimum temperature (Tmin), and monthly precipitation (Ppt) from 1982-2008 for each country except for Myanmar due to poor data availability where we used only two station data. The locations and the names of the weather stations are shown in Table 3.2.1.

Table 3.2.1. List of weather stations and their locations.

Station no	Station location	Country	Latitude	Longitude
72546	DES MOINES, IA.	USA	41.53 N	93.65 W
72450	WICHITA/ MID-CONTINEN, KS.	USA	37.65 N	97.43 W
72530	CHICAGO/O'HARE, IL.	USA	41.98 N	87.9 W
72434	ST.LOUIS/LAMBERT, MO	USA	38.75N	90.37 W
72235	JACKSON/ALLEN C.THO, MI	USA	32.32N	90.08 W
83526	CATALAO	BRAZIL	18.16 S	47.97W
83936	SANTA MARIA	BRAZIL	29.69 S	53.7 W
83339	CAETITE	BRAZIL	14.04 S	42.62W
83405	CACERES	BRAZIL	16.04 S	57.68 W
83483	PIRAPORA	BRAZIL	17.34 S	44.95 W
17022	ZONGULDAK	TURKEY	41.45 N	31.79 W
17060	ISTANBUL	TURKEY	40.97 N	28.81 W
17128	ANKARA	TURKEY	40.12 N	32.97 W
17244	KONYA	TURKEY	37.97 N	32.54 E
17280	DIYARBAKIR	TURKEY	37.88 N	40.17 E
38062	KZYL-ORDA	KAZAKHSTAN	44.77 N	65.52 E
38081	TASTY	KAZAKHSTAN	44.8 N	69.11 E
38198	TURKESTAN	KAZAKHSTAN	43.27 N	68.21 E
38341	DZAMBUL	KAZAKHSTAN	42.85 N	71.37 E
42369	LUCKNOW	INDIA	26.75 N	80.87 E
42647	AHMADABAD	INDIA	23.07 N	72.62 E
42754	INDORE	INDIA	22.72 N	75.79 E
42875	RAIPUR	INDIA	21.23 N	81.64 E
43014	AURANGABAD CHIKALTHA	INDIA	19.85 N	75.39 E
47008	CHONGJIN	N. KOREA	41.78 N	129.81 E
47014	CHUNGGANG	N. KOREA	41.78 N	126.87 E
47041	HAMHEUNG	N. KOREA	39.93 N	127.54 E
47058	PYONGYANG	N. KOREA	39.03 N	125.77 E
47105	KANGNUNG	S. KOREA	37.75 N	128.89 E
47108	SEOUL	S. KOREA	37.57 N	126.96 E
47146	CHONJU	S. KOREA	35.82 N	127.14 E
47159	PUSAN	S. KOREA	35.1 N	129.02 E
47184	CHEJU	S. KOREA	33.52 N	126.52 E
48008	MYITKYINA	MYANMAR	25.37 N	97.39 E
48042	MANDALAY	MYANMAR	21.98 N	96.09 E
48327	CHIANG MAI	THAILAND	18.78 N	98.97 E
48381	KHON KAEN	THAILAND	16.43 N	102.82 E
48400	NAKHON SAWAN	THAILAND	15.8 N	100.16 E

Station no	Station location	Country	Latitude	Longitude
48407	UBON RATCHATHANI	THAILAND	15.25 N	104.86 E
48500	PRACHUAP KHIRIKHAN	THAILAND	11.83 N	99.82 E
48820	HA NOI	VIET NAM	21.02 N	105.79 E
48845	VINH	VIET NAM	18.7 N	105.66 E
48855	DA NANG	VIET NAM	16.03 N	108.17 E
48870	QUI NHO'N	VIET NAM	13.77 N	109.21 E
48900	HO CHI MINH	VIET NAM	10.82 N	106.66 E
50953	HARBIN	CHINA	45.75 N	126.76 E
54342	SHENYANG	CHINA	41.77 N	123.42 E
54511	BEIJING	CHINA	39.93 N	116.27 E
54823	JINAN	CHINA	36.68 N	116.97 E
58321	HEFEI	CHINA	31.87 N	117.22 E
96035	MEDAN	INDONESIA	3.57 N	98.67 E
96221	PALEMBANG	INDONESIA	2.89 S	104.69 E
96933	SURABAYA	INDONESIA	7.21 S	112.71 E
97260	SUMBAWA BESAR	INDONESIA	8.42 S	117.41
97502	SORONG	INDONESIA	0.92 S	131.11 E
47412	SAPPORO	JAPAN	43.05 N	141.32 E
47584	MORIOKA	JAPAN	39.7 N	141.16 E
47615	UTSUNOMIYA	JAPAN	36.55 N	139.86 E
47761	HIKONE	JAPAN	35.27 N	136.24 E
47807	FUKUOKA	JAPAN	33.58 N	130.37 E

3.2.2. 3. Analysis of Data

Soybean area (ha), production (tonnes) and yield (t/ha) data from 1982-2008 were first divided into 3 period for comparison each consisting of 9 years namely as: 80s from 1982- 90, 90s from 1991-1999 and 00s from 2000-2008.

In case of climatic variables, values of solar radiation (Rs) was calculated from mean monthly values of maximum (Tmax) and minimum temperature (Tmin) difference using Hargreaves-Samani model (1982) with the following equation (details are discussed in the section 3.1) –

$$R_s = K_{Rs} \times R_a (T_{max} - T_{min})^{0.5}$$

Where R_s is mean monthly solar radiation, R_a is the extra terrestrial solar radiation, $(T_{max} - T_{min})$ is the range of mean monthly Maximum and minimum temperature variation and K_{Rs} is the Hargreaves-Samani co-efficient (0.16 for inland regions).

Annual mean of monthly average temperature, maximum temperature, minimum temperature, solar radiation and cumulative precipitation were calculated for each year and country and divide them into 3 time periods (80s, 90s, and 00s). Regression analysis was performed using the average yield value of each period for 13 countries with the climate factors like average temperature, precipitation etc. of the respected time period in order to establish some relation between yield and climate variability. Precipitation data were excluded for Myanmar and India because of unavailability and poor quality.

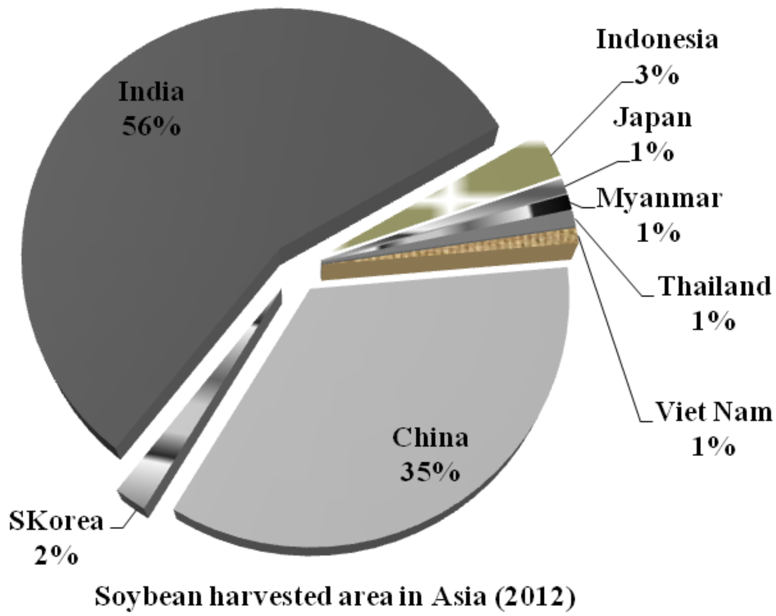
3.2.3. Results

3.2.3. 1. Harvested area, production and yield trend

World soybean production has been increasing since 1960 with a rapid speed of almost 30% - 40% increases per decade (Masuda and Goldsmith, 2009)

The total production area of soybean varies from one country to another and also with time to time. According to FAO (2012) data, 10 countries of Asia (Fig 3.2.2.) constitutes the whole production and majority (89%) of that comes from China and India and rest come from Indonesia, South Korea, Japan, Thailand, Vietnam, Myanmar, Iran and Kazakhstan. However, relative proportion of land area employed for cultivation is not same as the production. Although 47% of whole Asian production comes from China but the land area exploited for this purpose is only 35% of the total soybean harvested area of Asia. On the contrary, India has to use 56% of the total land area in order to reach 42% total production indicating that they have to use 21%

a)



b)

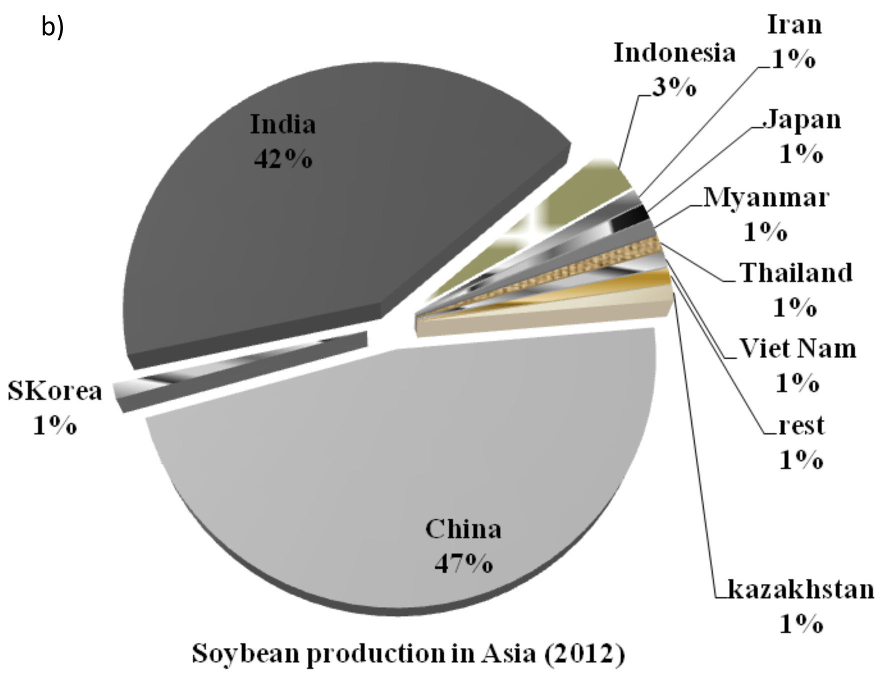


Fig. 3.2.2. Relative distribution (percentage basis) of major soybean producing countries of Asia: a) harvested area, b) total production.

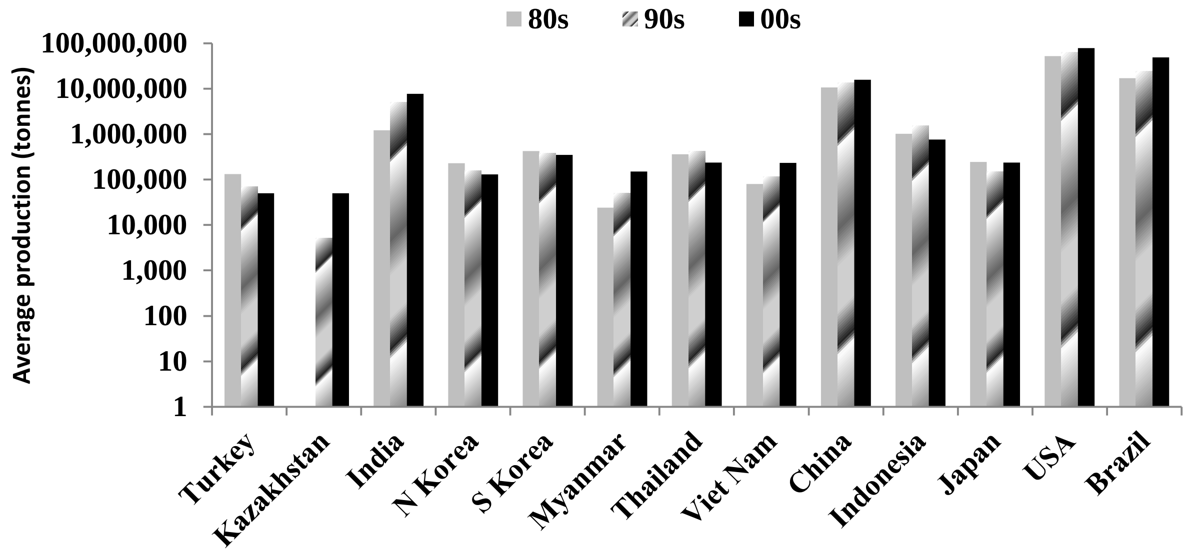


Fig 3.2.3. Country wise production trend in 3 periods; 80's = 1982-1990, 90s = 1999-00, 00's = 2000-2008.

more land to catch up with China's production (Fig 3.2.3). The reason for this is the yield gap or variation between the countries which also varies significantly among the countries and with time.

Production and harvested area and yield trend over the last 27 years which has been divided into 3 periods: 80s, 90s and 00s showed quite distinctive picture for different countries of Asia as oppose to USA and Brazil (Fig 3.2.3 and 3.2.4, 3.2.5). During the whole period china has been the leading producing country followed by India in Asia while USA and Brazil remain constantly the highest two in the world. Kazakhstan showed dramatic increase (within in 1 decade) in terms of production and area followed by India, Myanmar and Vietnam while Turkey, North Korea and Thailand showed decreasing trend. Production and harvested area in rest of the countries (China, Japan, Indonesia, South Korea) remain fairly stable with little increasing trend like USA and Brazil. In terms of yield trend, all the countries showed consistent increase except for South Korea which showed little decrease over the whole time period. The highest yield in recent years among the countries are found in Turkey (3.33 t/ha in 00s) even higher than USA (2.68 t/ha) and Brazil (2.57 t/ha). China and Japan exhibited almost same yield (1.69 and 1.68 t/ha) and ranked fourth. Lowest yield were observed in India (1.01 t/ha in 00s) and Myanmar (1.12 t/ha in 00s)

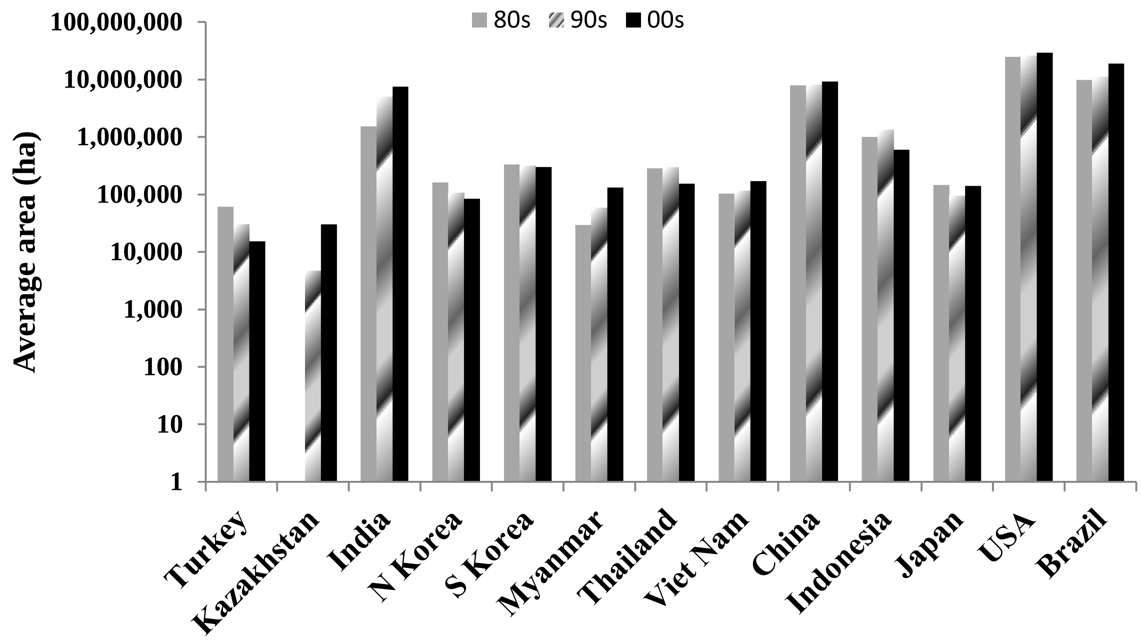


Fig 3.2.4. Country wise harvested area trend in 3 periods; 80's = 1982-1990, 90s =1999-00, 00's = 2000-2008.

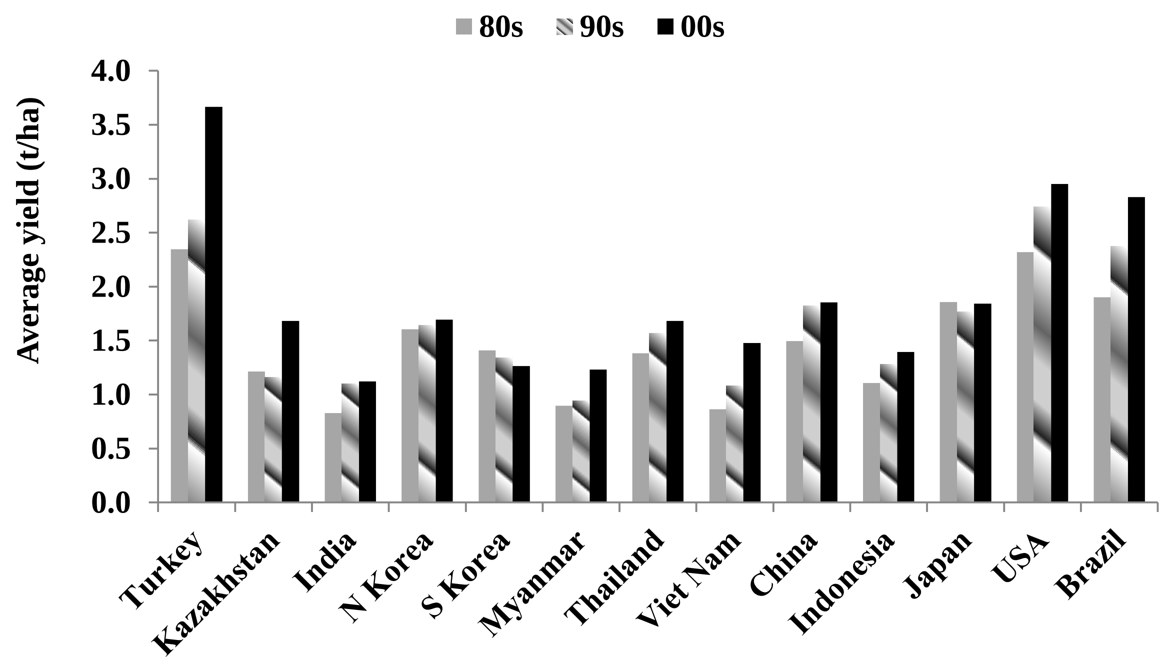


Fig 3.2.5. Country wise yield trend in 3 periods; 80's = 1982-1990, 90s =1999-00, 00's = 2000-2008.

while other countries had intermediate yield.

During the period from 80s to 90s India tripled its production by doubling their harvested area and with remarkable 33% yield increase. Myanmar and Indonesia followed the same sharp trend and improve production 111% and 25% mostly by increasing area by 98% and 33%. Yield increase contribute very little to reach that production mark as only 16% and 5% improvement was noted in the respective countries. Alternatively, Vietnam and China increased production up to 43% and 28% mainly by improving yield by 26% and 22% and with little area increase (13% and 3%). During this period USA raised production 24% by improving yield up to 18% while Brazil improve 43% by increasing both harvested area (14%) and yield (25%). However, a reverse trend for production was observed in the some other countries during this period with decrease of harvested area particularly for Japan, South and North Korea and Turkey with 39%, 9%, 32%, and 29% reduction. In case of Japan and South Korea yield also decrease little (5%) with area causing reduction in total production but in Turkey (12%up) and North Korea (4%) yield trend was clear positive when production decreased .In fact, Turkey had the 2nd highest yield in world after USA.

During the period from 90s to 00s dramatic increase of production was noticed for Kazakhstan which was almost 10 fold higher with 5 fold increase in production area and a startling 45% raise in yield. Myanmar had the 2nd largest increase during this period in production with 3 fold increase accompanied by almost 2 fold increase in production area and 31% increase in yield. Vietnam also improved production significantly with combination of 47% and 36% raise in area and yield. Japan and India increase production during this period mainly by increasing production area as yield improvement was not significant. Brazil also increase production immensely mostly by increasing land area (69%) and only little by improving yield (19%). In case of USA, production improves 22% mainly due to area (14% up) than yield (8% up). Thailand, Indonesia, Turkey and North Korea showed a little negative trend during this period with loss of nearly 50% of harvested land though yield was improving consistently with time. Turkey exceeded the yield of USA and Brazil who have been consistently highest two in yield in world. North Korea and Thai land also had reasonably positive yield trend during this period. As seen from this observations production increase seems to mainly result from area improvement and to some extent to yield improvement. Although production is much lower than USA but

Turkey over the 2 periods (80s and 00s) showed little better yield and USA ranked close 2nd Brazil consistently had the 3rd highest yield over the 3 periods. Japan and China among the other countries had better yield followed by North Korea. India and Myanmar had consistently lowest yield over the 3 periods which is lower than highest yield of that period by 50% or more.

3.2.3. 2. Relation between climate factors and yield

Countries selected for study have widely different climate than each other even when they are located in the same continent like India and China. The most distinguishing feature of these climates is different in annual average temperature and precipitation. In general, based on the annual average temperature range these countries can be divided into two groups: one having annual temperature range from 22^0-30^0C like Brazil, India, Indonesia, Myanmar, Thailand, Vietnam and another having 8^0-15^0 C like Turkey, Kazakhstan, USA, Japan, China, North Korea, and South Korea (Fig 3.2.6). Annual total precipitation range among these countries varies from below 50 cm to more than 250 cm range (Fig 3.2.7). Countries with lowest annual precipitation are Kazakhstan, Vietnam and Turkey and countries with highest annual precipitation are India and Myanmar (not shown in Fig) followed by Thailand and Indonesia rest of the countries have annual precipitation range of 500-1000 mm. This differentiation of temperature and precipitation indicates that countries with lower yield like India, Myanmar usually have higher annual temperature and precipitation than countries with higher yield like USA, Turkey. On contrary, Brazil regardless of having higher annual temperature has a consistently good yield trend. This indicates for indentifying the climate yield relation it is necessary to consider annual highest and lowest temperature variation with average temperature.

The relation between yield and annual mean temperature, maximum temperature and minimum temperature during the 80s are shown in Fig 3.2.8 (a-c) while relation between solar radiation and precipitation are shown in Fig 3.2.8 (d, e). During this period yield showed a significant negative response ($r = -0.65$ to -0.60) toward average, maximum and minimum temperature but the response was not exactly linear rather non linear or quadratic in nature which is similar to the nonlinear response pattern previously found toward temperature (Schlenker and Roberts 2009; Tanura et al., 2008; Thompson 1970). Yield also showed nonlinear negative response toward

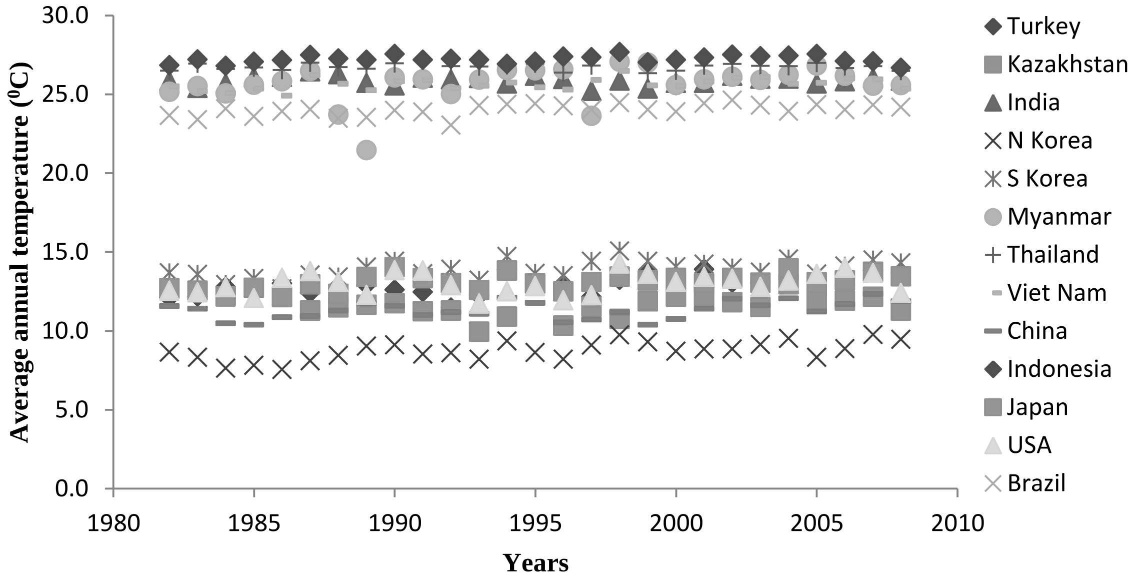


Fig. 3.2.6. Annual temperature variation among different soybean producing countries.

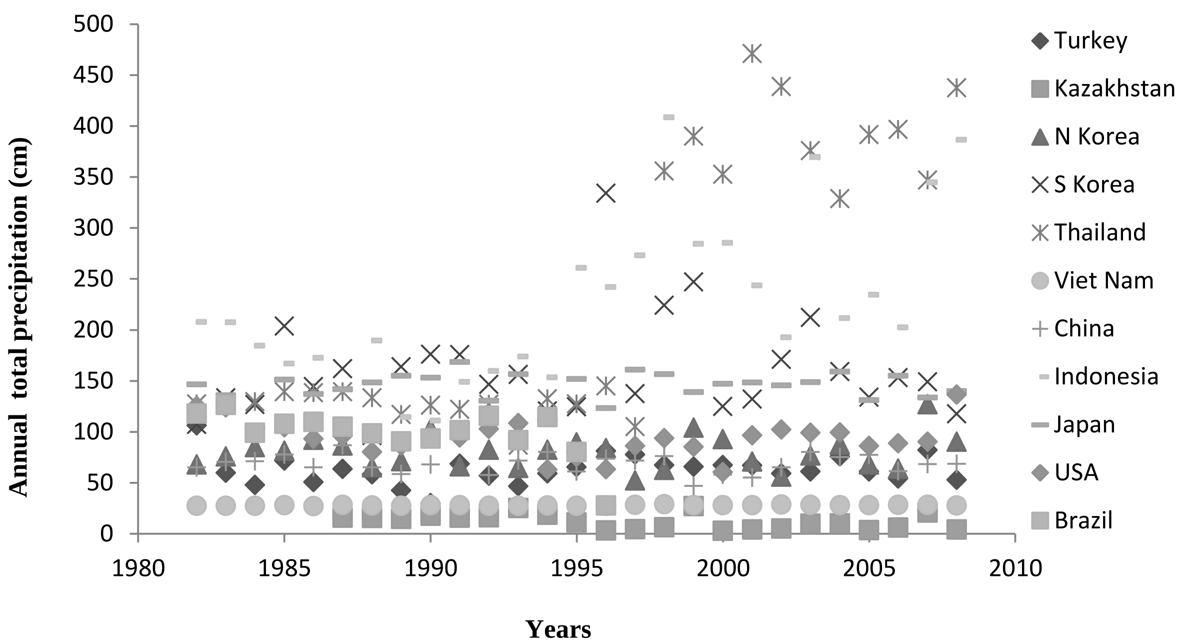


Fig 3.2.7. Annual precipitation variation among different soybean producing countries.

total precipitation due to wide range of variation. Relation between solar radiation and yield is somewhat ambiguous during this period. However, excluding the high yielding countries (USA, Brazil, and Turkey) a little negative relation with solar radiation can be found.

During the 90s the relation between yield and the climatic factors did not change much. Similar negative relation like 80s was observed for temperature and yield (Fig 3.2.9.a-c) but the association was lower (r = -0.41). Precipitation, average, maximum and minimum temperature and even solar radiation showed non linear negative response to some extent (Fig 3.2.9.d, e).

Nonlinear negative response to almost all the climatic parameters (average, maximum, minimum temperature, precipitation) was also obvious from the most recent period (Fig 3.2.10.a-e). During all the period, annual maximum temperature seems to affect yield more seriously than other climate parameters. When we try to correlate yield with the comparatively hottest months (summer months) of the years we found clear linear negative response in almost all the period (Fig 3.2.11, 3.2.12, 3.2.13). Since we consider only 2 hottest months of the year temperature variation range was reduced and linear decline of yield with increasing temperature was found. Almost in all period yield did not reach above 1.5 t/ha when average summer temperature crosses 25^0 C in most countries except for Brazil in 00s (Fig 3.2.13a).This relation is also evident from summer months minimum and maximum temperature (Fig 3.2.11, 3.2.12, 3.2.13) in all locations. Yield decreases sharply even at the highest yielding countries with the increase of summer season temperature.

Even though annual pattern of solar radiation did not showed significant relation with yield (including all the high yielding countries) average solar radiation of summer months affects yield positively; in fact clear pattern of linear response is observed for all 3 periods (Fig 3.2.10 d, 3.2.11 d, 3.2.12 d). Annual rainfall pattern (Fig 3.2.7 e, 3.2.8 e, 3.2.9 e) showed that yield increases almost linearly with increasing precipitation until it reaches 1000 mm; beyond this point yield start to decrease with increasing precipitation. When summer month’s precipitation was considered it became more obvious that yield decreases when summer rainfall exceeds 2000 mm. Interesting relations between annual average temperature and precipitation was found which can be party useful to explain the yield variation (Table 3.2.2). Some locations like Vietnam, Japan, North and South Korea average temperature showed positive correlation with

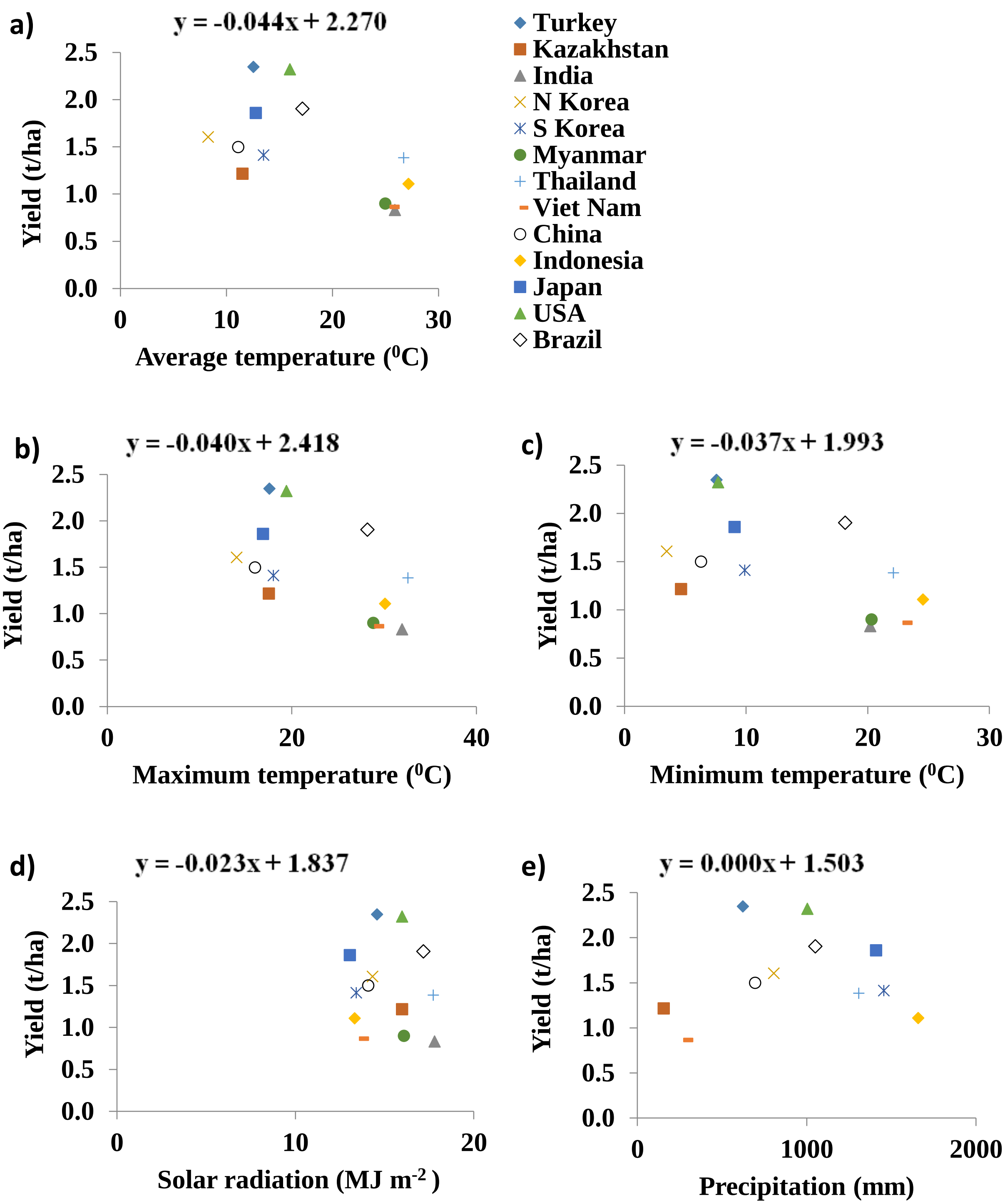


Fig. 3.2.8. Scatter plot matrix illustrating relation between average soybean yield of 80s (1982-90) with average temperature (a), maximum temperature (b), minimum temperature (c), solar radiation (d), total precipitation (e) in Asia.

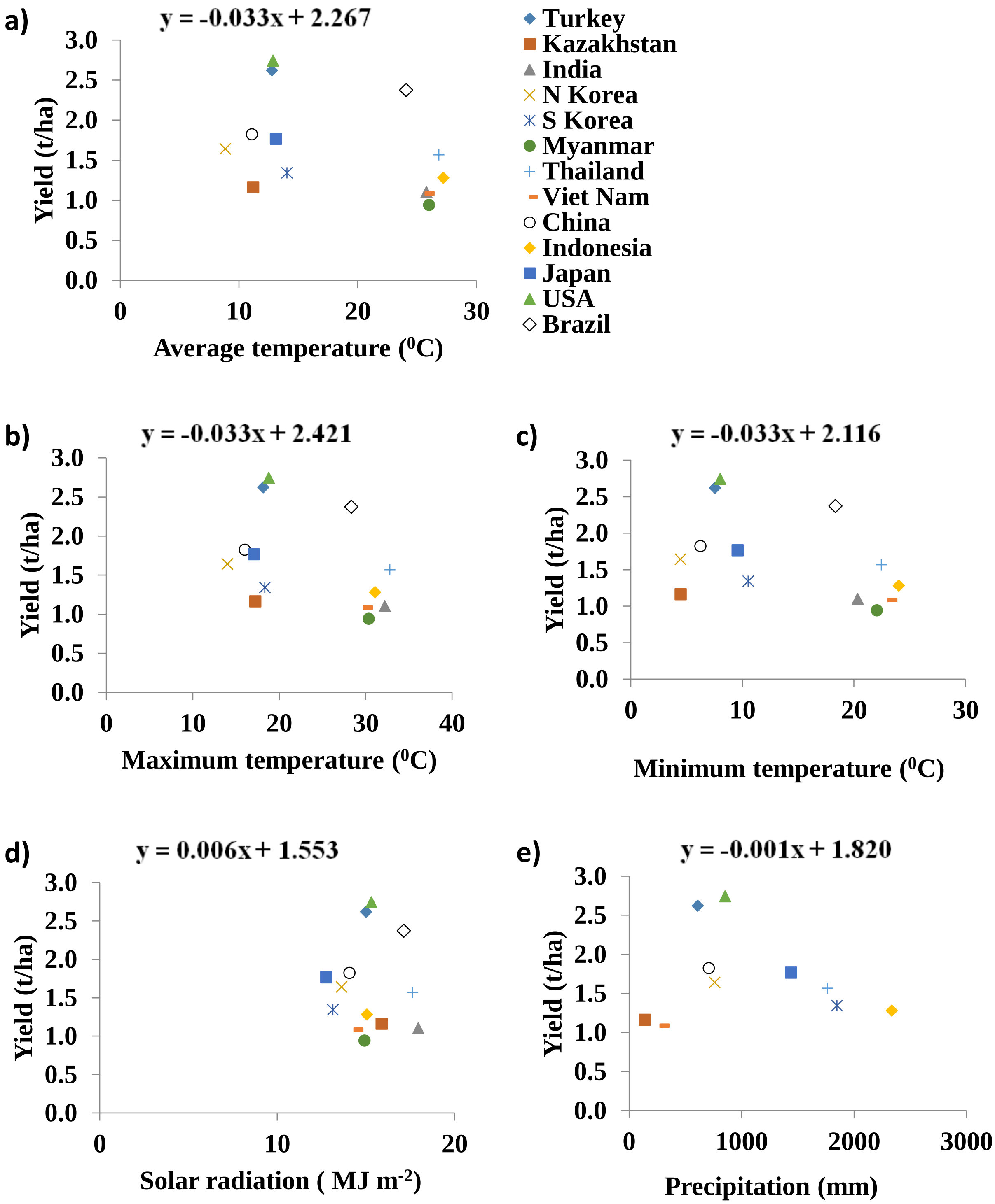


Fig. 3.2.9. Scatter plot matrix illustrating relation between average soybean yield of 90s (1991-99) with average temperature (a), maximum temperature (b), minimum temperature (c), solar radiation (d), total precipitation (e) in Asia.

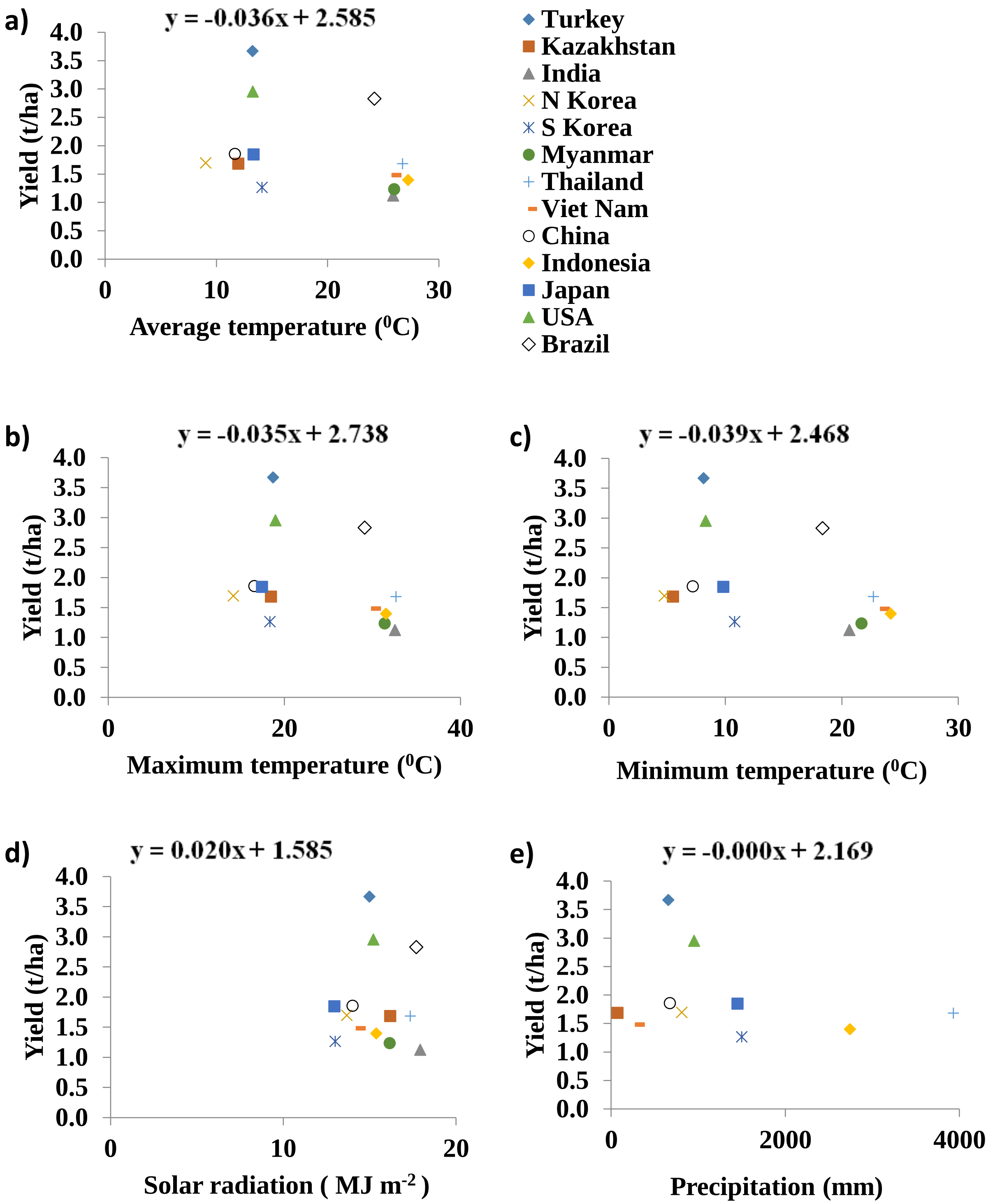


Fig. 3.2.10. Scatter plot matrix illustrating relation between average soybean yield of 00s (2000-08) with average temperature (a), maximum temperature (b), minimum temperature (c), solar radiation (d), total precipitation (e) in Asia.

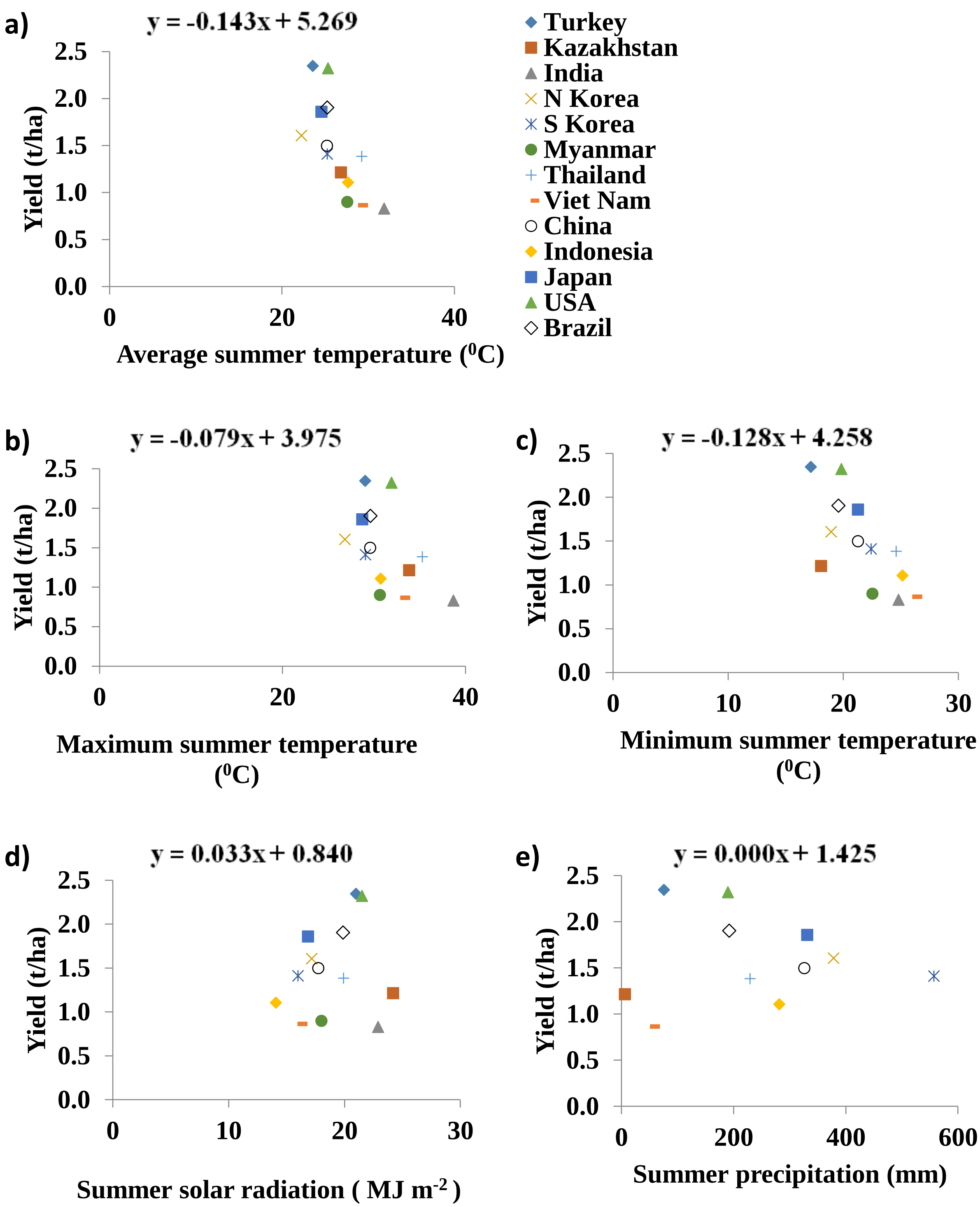


Fig. 3.2.11. Scatter plot matrix illustrating relation between average soybean yield of 80s (1982-90) with summer average temperature (a), maximum temperature (b), minimum temperature (c), solar radiation (d), total precipitation (e) in Asia.

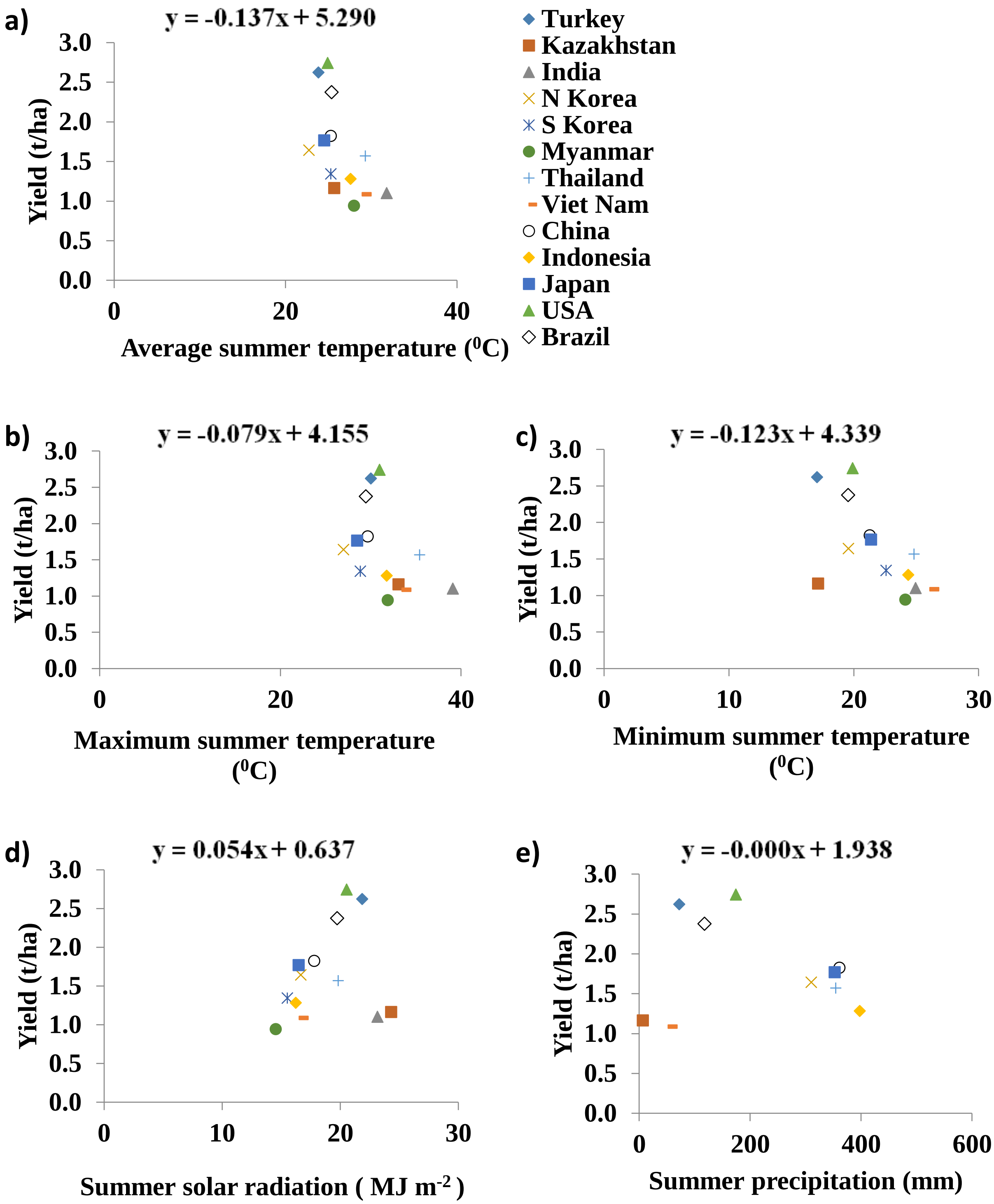


Fig. 3.2.12. Scatter plot matrix illustrating relation between average soybean yield of 90s (1991-99) with summer average temperature (a), maximum temperature (b), minimum temperature (c), solar radiation (d), total precipitation (e) in Asia.

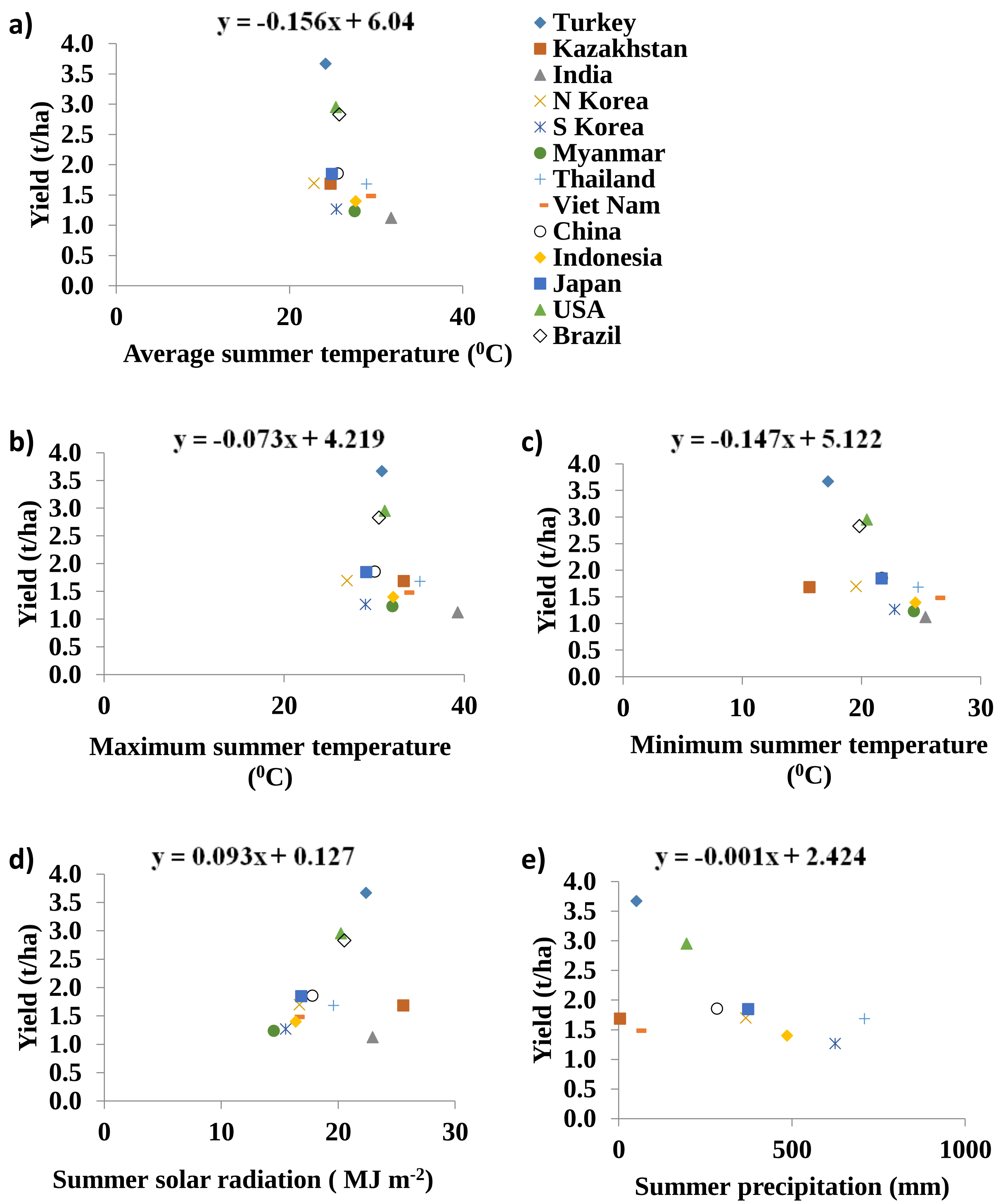


Fig. 3.2.13. Scatter plot matrix illustrating relation between average soybean yield of 00s (2000-08) with summer average temperature (a), maximum temperature (b), minimum temperature (c), solar radiation (d), total precipitation (e) in Asia.

precipitation which indicates yield reduction from the high average temperature is likely to be accompanied with yield reduction from excess precipitation whereas due to negative correlation in USA, Brazil, Kazakhstan yield reduction might result from high temperature and low rainfall simultaneously.

3.2.4. Discussion

Positive trend of Asian soybean production and yield is clearly evident (Fig 3.2.3, Fig 3.2.5) in all three period. Positive yield trend is mostly responsible for gross production improvement in the 3 decades as harvested area remained almost unchanged or reduced in some countries (Fig 3.2.4). Total production in Asia increased 27% and 15% in last two decade compare to the previous one as a result of 8% and 14% increase in yield from the previous decade. This also indicates that yield improvement rate per decade is quite sharp and interestingly little higher than global yield improvement (10%) rate per decade in the 2000s while it was much lower than global yield improvement (40%) rate per decade (Lobell and Gourdji, 2012).

Countries that are located in the lower annual temperature zone also seem to have higher yield than countries that are in higher temperature zone. Negative impact of higher temperature on yield becomes quite evident from the annual Maximum temperature (Fig 3.2.8 b, 3.2.9 b, 3.2.10 b) and summer average temperature (3.2.11 a, 3.2.12 a, 3.2.13a) relation. Time series regression analysis of yield with average temperature for particular place generally shows a positive trend which is a common tendency of the model (Lobell, 2007). Therefore using multiple sites (countries) and multiple years (3 periods) data as such in this analysis reduces the error and shows a general relation of crop climate for a broader region. It implies that in Asia countries having higher average annual temperature (India, Myanmar, and Indonesia) suffers from negative yield response and with future tendency of increasing temperature the problem will be more prominent which is also projected in some other studies (Lobell, 2008) whereas at the same time countries having lower annual temperature like Turkey, China etc. are not affected by negative yield response as much as the previous group rather positive relation has been reported for some regions in some studies (Tao et al., 2008). However, yield can be hampered negatively not only by high annual mean temperature but also by short episodes of extremely high temperature during the growing season or heat wave (Ciais et al., 2005). From the last 3 decades (1982-2008) this negative relation between increasing temperature and soybean yield did not change which indicates this relation is quite stable and potentially threatening issue for increasing soybean production and yield to meet up future demand. Annual temperature above 25^0C in almost all locations reduces yield. The relation between summer average temperature and yield in all 3 period portrays fairly damaging picture where rise in summer average temperature of about 1^0C and 2^0C from 25^0C is associated with 9% and 17% yield reduction in 80s and 90s (Fig 3.2.11a, 3.2.12a) and this value changed to 7% and 15% in 00s (Fig 3.2.13a). This little improvement in yield in the latest period may be contributed to adaptation. This estimation is closely related with the estimation by Lobell (2011) where 10% yield loss is expected for every 1^0C rise in temperature. However, this should be mentioned that climatic factors influences yield concomitantly (Table 3.2.2); as such this yield reduction can arise from not only due to summer temperature but also due to the negative influence of summer precipitation.

Table 3.2.2. Relation between annual average temperature and precipitation in study regions.

Country	Turkey	Kazakhstan	N Korea	S Korea	Thailand	Viet Nam	China	Indonesia	Japan	USA	Brazil
Correlation coefficient, r	0.00	-0.19	0.16	0.08	0.00	0.91	-0.04	-0.01	0.27	-0.12	-0.49

The relation between precipitation and yield is not as dominant as temperature at all periods but significant negative relation with summer total precipitation have been found for 80s (r = -0.51) and 00s (r = -0.42). Annual precipitation affects positively until it reaches total of 150 ($\pm$50) cm then yield decreases with increasing precipitation. This non linear response is evident in all countries except for Vietnam and Kazakhstan where annual rainfall is very low and only positive response is observed. The frequency and period of rainfall is also important. When heavy rainfall coincides with soybean maturity and reproductive stage the relation is clear but otherwise it is difficult to identify the relation which may be the cause of obscure relation (Fig 3.2.11e) in some account. Yield and annual solar radiation did not showed significant relation while considering all the locations but the small negative relation that was found excluding the high yielding countries probably rise due to negative influence of temperature. During summer (Fig 3.2.10 d, 3.2.11 d, 3.2.12 d) solar radiation relate to yield positively. Summer temperature, precipitation and solar radiation showed linear and more distinct response toward yield than annual average climate parameters probably because it coincides closely with growing season climate. This study indicates that overall influence of high temperature on reducing yield has been more consistent and significant than precipitation in last 3 decades on soybean which is similar to the findings of other studies (Lobell et al., 2011)

In short, soybean yield variation among different countries of Asia occurs partly due to higher temperature and excessive rainfall. All this negative influence over yield along with decreasing or almost static harvested area in most countries creates a greater challenge to improve the production for this highly populated region. With a tendency of global warming future soybean production will be hampered seriously in the tropical parts of Asia and the yield difference will increase with North and South America.

Chapter 4

Experimental evaluation of high temperature effect on soybean yield formation

4.1. Introduction

Soybean (*Glycine max*) is the 3rd most important crop commodity in the world in terms of global trade (FAO, 2014). Reproduction plays an important role in the survival and succession of seed crop plant which depends largely on the environmental conditions prevailing during the growth season (Boyer and Westgate, 2004). Soybean reproductive growth is sensitive to temperature. Several studies has been carried out to investigate the impact of high temperature stress on soybean yield (Gibson and Mullen, 1996; Ferris et al., 1999; Shiraiwa et al., 2006; Thomas et al, 2010; Tacarindua et al., 2012) but very few relates the yield reduction with reproductive damage.

Seed set in bean primarily depends upon function of pollen and ovule, successful pollination, fertilization and post-fertilization processes. Although the range of temperature tolerance threshold is highly variable between species, mild increases in temperature negatively affect characteristics such as pollen viability (Devasirvathama et al., 2013; Aloni et al., 2001; Erikson and Markhart, 2002), pollen germination ability (Salem et al., 2007; Koti et al. 2005; Prasad et al., 2002), pollen tube growth rate (Salem et al, 2007) and seed and fruit set (Sato et al., 2002; Aloni et al., 2001). Pollen development during various phases of microsporogenesis has been found sensitive to high temperature stress in soybean (Salem et al., 2007; Koti et al., 2005; Djanaguiraman et al., 2013).

However, in the field high temperature stress is often accompanied by water stress (Moffat 2002; Shah and Paulsen 2003). Recent studies (Rizhsky et al., 2004; Mittler 2006) have revealed that responses of plants to a combination of two different environmental stresses is unique and cannot be directly extrapolated from the response of plants to each of the different stresses individually (Barnabás et al., 2008). However, relatively little is known about how their combination impacts soybean and particularly reproduction. In addition, recent pattern of global climate change is expected to raise temperatures, change the distribution of precipitation and intensify drought

(Wigley and Raper 2001). The objective of this study was to investigate the effects of high temperature and combined stress of high temperature and mild drought on soybean yield and corresponding pod set and pollen germination in a field like condition. Temperature gradient chambers (TGCs) allow the study of temperature effects on crops under field-like conditions, where the inside temperatures tend to keep track with the ambient temperatures (Horie et al., 1995).

4.2. Materials and methods

4.2.1. Environment description

Soybean cultivars were grown under various temperatures inside TGCs at the Experimental Farm of Kyoto University at Kyoto City, Japan (35.0^0 N latitude, $135.5^0 6'$ E longitude, 71 m above sea level). The TGC, which was 2 m wide and 25 m long, created a nearly linear temperature gradient along its longitudinal axis which is from near ambient to a temperature that was several degrees higher, while maintaining the natural diurnal changes in air temperature. The chambers were covered with polyethylene terephthalate film with a light transmittance of 80% (Horie et al., 1995; Tacarindua et al., 2012). Temperature fluctuation was monitored regularly and noted. The soil used is classified as alluvial sandy loam (Fluvic Endoaquepts) .We use 2 TGC as control treatment where well watered condition was maintained and another 2 TGC as drought treatment where water treatment was imposed.

4.2.2. Plant Materials and treatments

Soybean cultivar Stressland, Tachinagaha, Enrei in 2011 and cultivar Stressland, Fukuitaka, UA4805 and Enrei in 2012 was used to study the effect of high temperature and water stress. Two temperature treatments: ambient temperature and high temperature (ambient temperature + 2°C) were used in 2011 and 2012. Water stress (drought) was employed in the beginning of flowering in 2012. Volumetric water content was maintained at approximately 24% or above for control treatment while water stress or drought stress was applied by withholding water supply for few days until it dropped to 15%. Soil moisture content was monitored using a TDR, time domain reflectometer, (SONY Tektronix Co. Ltd., Tokyo, Japan) installed at a depth of 30 cm.

4.2.3. Plant husbandry

Soybean seeds were directly sown on July 12, in 2011 and 2012 into the soil culture bed in two TGCs, arranged in furrows of 0.25 m wide, 24 m long, and 0.25 m intra-row spacing. Irrigation was carried out through the drainage pipe located 50 cm below the soil surface in TGC to raise the water table and was evenly distributed throughout the entire soil culture bed. The plants were kept healthy and weed free throughout the growing season by hand weeding and chemicals. Insecticides were used to prevent aphids *(Aphis fabae scopoli)* and red spider mite *(Tetranychus urticae koch)*. Seeds were inoculated with *Rhizobium* prior to sowing and soil was fertilized with standard rate of P and K fertilizer and at the same time nematicide was incorporated into soil.

4.2.4. Measurement

4.2.4.1. Pollen germination measurement

Soybean flowers (10-15) on the day of anthesis were randomly collected from 5 plants in each cultivar between 0800 and 900 hr as it is optimum time for flower opening in Japan (Kitano et al., 2006). Because of differences in flowering dates, in vitro Pollen germination tests were conducted during 11 to 14 August and 22-25 August, 2012 in early and late-flowering varieties respectively. Flowers collected were air-dried for 1hour, germination medium was prepared and pollen was dusted onto the germination medium as per method described in Salem et al. (2007) and incubated for 24 hour at 30^0C as it is considered optimum temperature for germination. Pollen grains were counted (5 fields per petridish) for germination using a microscope (Olympus SZ61-29, USA). Pollen grain was considered germinated when its tube length equaled the grain diameter at 6.7x magnification. Germination was calculated by counting the total number of pollen grain (on average 100-200) in a microscope field to the number of pollen germinated there and averaged across 4 fields per Petri dish.

4.2.4.2. Photosynthesis and conductance measurement

Photosynthetic rate and stomatal conductance were measured on a clear sunny day between 900-1300 hr in the central leaflets of fully developed leaves of three plants per treatment once a week from near flowering using LI-6400 (LI-COR, Inc., Lincoln, NE, USA).

4.2.4.3. Yield and pod set measurement

At Maturity, 5 plants from each cultivar were collected and node number, flower number, pod number per plant were recorded. Flower number was counted by counting pods and by abscission scars for aborted flowers (Dybing, 1994) and pod set ratio was calculated as the ratio of pod number to flower number per plant. Plants were separated into component parts-stems, pod shells, seeds and their respective dry weight was achieved by oven drying for more than 72 hour at 80^0C and used to calculate final seed size, seed number, seed yield and harvest index (HI).

4.2.4.4. Carbon isotope discrimination (CID) measurement

The carbon isotope discrimination of milled seed samples (0.5 mg) collected at maturity from all the cultivar and determined by mass spectrometry (Delta V; Thermo Fisher Scientific) at Kyoto University Ecological Center. Carbon isotopic composition of seed was expressed relative to the standard Pee Dee Formation of Belemnite. Carbon isotope compositions of the seeds (δ^{13}C) were converted to carbon isotope discrimination (Δ^{13}C) using the formula by Farquhar et al. (1982):

$$\Delta^{13}C = (\delta^{13}C\ atm - \delta^{13}C\ plant)/\ (1+\delta^{13}C\ plant)$$

δ^{13} C atm = Carbon isotope composition of air (-8‰)

δ^{13}C plant = Carbon isotope composition of seeds (measured value)

Δ^{13}C were multiplied by 1000.

4.2.5. Statistical analysis

The effects of increased air temperature and drought on pollen germination, seed yield, pod set and yield components, were evaluated using an analysis of variance (ANOVA).

4.3. Results

4.3. 1. Temperature, vapor pressure deficit, water stress

Average temperature and vapor pressure deficit (VPD) during the growing season is shown in Table 4.1 which indicated under high temperature stress VPD increases. During R1 to R5 (flowering to pod setting stage) high temperature treatment was 31^0C and 30^0C in 2011, 2012 while ambient temperature treatment was 27^0C and 28^0C in 2011 and 2012. It should be mentioned that in 2011 for few days during R1-R5 ambient temperature was nearly 34^0C and correspondingly high temperature treatment was nearly 38^0 -39^0C. As a result, VPD during R1-R5 period in both years were very high (1.4-1.3 kpa). For drought treatment, soil moisture content was maintained around 17-14% while under control treatment it was 20-25% in both years. This water stress condition exacerbated temperature in each treatment by 0.2^0C than control in all experiment (not shown in table).

Table 4.1. Growing season average temperature and vapor pressure deficit (VPD) in 2011, 2012.

Tempearture treatment	Growing season average temperature (^{0}C)		Growing season average VPD (Kpa)	
	2011	2012	2011	2012
Ambient	24	27	0.4	0.6
High	28	29	1.2	1.4

4.3. 2. Pollen germination

In vitro Pollen germination study conducted in 2012 for all cultivars under high temperature stress (Fig. 4.1a) and combined high temperature and water stress condition (Fig. 4.1b) showed different degree of response. Significant reduction of germination was found from ANOVA study under combined high temperature and drought condition ($P>0.05$). Pollen germination was reduced on average 6-15% under temperature treatment, 14-23% under drought treatment and 25-30% under combined temperature and drought treatment in all cultivar. Most resistance cultivar toward combined stress was UA4805 and most susceptible was Tachinagaha.

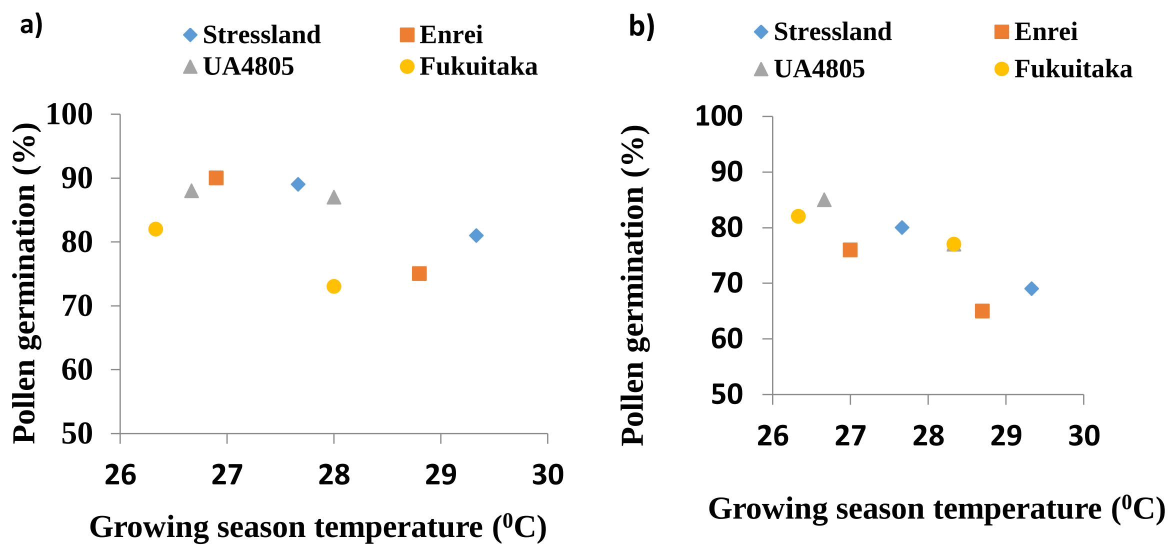


Fig. 4.1. Effect of (a) increased temperature (b) increased temperature and water stress on pollen germination of soybean grown in TGC.

4.3. 3. Flower, pod set and other yield component

Under high temperature stress total pod number, pod set ratio, seed size and ultimately seed yield was significantly affected (Table 4.2, 4.3).

Table 4.2. Effect of high temperature stress on soybean cultivar Enrei, Stressland, Tachinagaha.

Cultivar	Temperature treatment	Plant height	Node $/m^2$	Flower $/m^2$	pod/ m^2	podset ratio	Seed $/m^2$	Seed size (mg)	Seed yield (g/m^2)	HI
Tachinagaha	ambient	38	528	1518	912	0.60	1530	305	466	0.62
	high	41	450	1407	554	0.39	657	245	161	0.46
Stressland	ambient	125	1270	5044	3240	0.64	7180	140	1003	0.57
	high	134	1114	4548	2268	0.50	4058	138	560	0.54
Enrei	ambient	49	561	1602	1162	0.73	1844	262	483	0.56
	high	40	477	1364	812	0.60	1442	233	336	0.53
ANOVA										
Temperature		0.83	0.39	0.69	0.14	<0.01	<0.1	<0.01	<0.05	0.11
Cultivar		<0.001	<0.01	<0.05	<0.01	<0.05	<0.01	<0.001	<0.05	0.51
Temp X CV		0.25	0.95	0.97	0.69	0.38	0.30	<0.05	0.51	0.30

Table 4.3. High temperature and water stress effect on 4 soybean cultivar.

Cultivar	Treatment water	Treatment Temp	Plant height	Node no/ m^2	Flower / m^2	Pod / m^2	pod set ratio	Seed number / m^2	seed size (mg)	Seed yield (g/m^2)	HI
Stressland	Control	Ambient	106	946	2980	1574	0.55	3352	143	481	0.59
		High	106	770	2422	1296	0.54	2920	137	399	0.58
	Drought	Ambient	96	841	2423	1275	0.53	3025	120	363	0.55
		High	96	709	1932	770	0.39	1733	106	183	0.49
Enrei	Control	Ambient	55	713	1400	1026	0.73	1641	245	435	0.49
		High	52	650	1285	887	0.68	1458	235	366	0.46
	Drought	Ambient	49	647	1393	887	0.64	1331	220	327	0.48
		High	52	610	1153	744	0.60	961	197	239	0.43
UA4805	Control	Ambient	80	615	2946	1379	0.49	2383	141	335	0.56
		High	81	546	2881	1033	0.36	1846	109	203	0.48
	Drought	Ambient	70	553	2502	1085	0.45	1938	132	256	0.56
		High	70	437	1799	654	0.36	1216	122	148	0.46
Futukuitaka	Control	Ambient	88	969	3665	1645	0.43	2509	261	651	0.55
		High	90	1041	4667	1746	0.37	2690	233	564	0.52
	Drought	Ambient	87	929	3435	1392	0.40	2407	214	527	0.48
		High	89	882	3033	1090	0.34	1942	175	330	0.40
ANOVA	(P value)										
Temperature(T)			0.80	0.14	0.24	<0.05	<0.05	<0.05	<0.01	<0.01	<0.01
Water (W)			<0.05	0.10	<0.01	<0.01	<0.05	<0.01	<0.001	<0.01	<0.01
Cultivar(Cv)			<0.001	<0.001	<0.001	<0.01	<0.001	<0.001	<0.001	<0.01	<0.01
T X Cv			0.99	0.64	0.32	0.57	0.78	0.49	0.62	0.94	0.47
WxCv			0.36	0.99	0.29	0.66	0.49	0.89	0.05	0.73	0.15
TxW			0.77	0.80	0.12	0.36	0.63	0.20	0.84	0.53	0.15
CvxWxT			0.96	0.92	0.40	0.88	0.52	0.88	0.72	0.91	0.96

However, under drought and temperature combined stress all the yield components (flower number, pod number, pod set ratio, seed number, seed size) were significantly affected. Pod set ratio reduction was much higher in 2011 than 2012 in all cultivar as the stress was more severe as mentioned earlier (Fig 4.2). In 2012, pod set ratio reduction was higher under combined stress condition than high temperature stress alone in all cultivar only except UA4805 where temperature stress was higher than the combined stress. In 2011, cultivar Tachinagaha was most sensitive to temperature stress and in 2012 UA4805 was most sensitive. On the other hand,

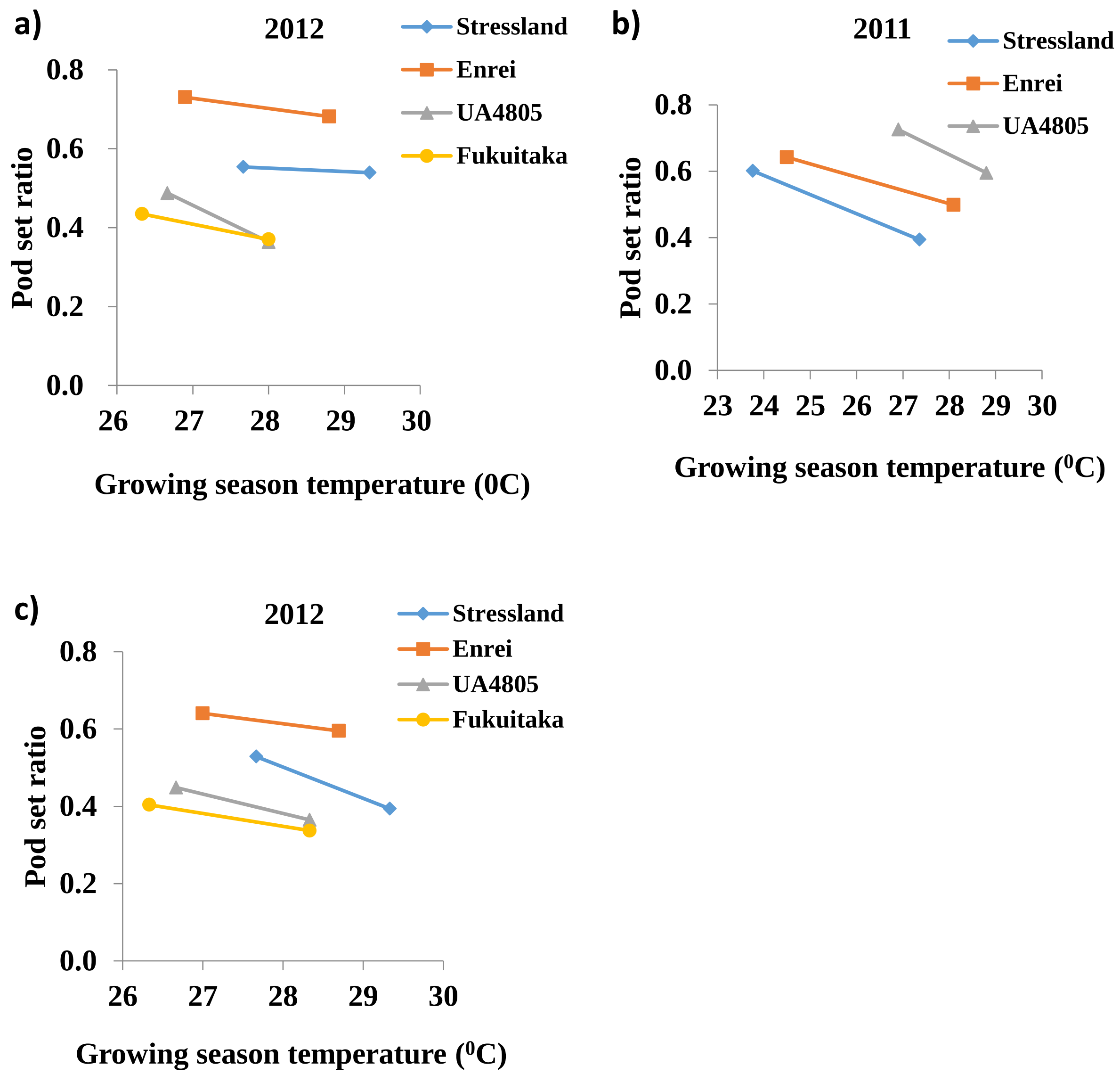


Fig. 4.2. Effect of high temperature (a-2012) (b-2011); high temperature and water stress (c-2012) on podset ratio of soybean cultivar.

cultivar stressland was most resistant to temperature stress but not under combined stress condition. Cultivar Fukuitaka was most resistant under high temperature stress and combined stress condition. On average 5-8% pod set ratio was reduced in 2012 under water and temperature stress and 16-18% in 2011. Seed yield reduced 13-39% due to high temperature stress in 2012 and 30- 65% in 2011 in different cultivar. In 2012, under combined stress condition seed yield reduced 27-50% in different cultivar. On average, 11-28% pollen germination reduction and associated 22-42% seed yield reduction was observed under high temperature stress and combined high temperature and water stress condition respectively.

4.3. 4. Photosynthesis and stomatal conductance

Under control condition photosynthesis rate was slightly affected by temperature stress but showed distinct decrease under combined stress in 2012 (Fig 4.3). The trends of photosynthesis rate change was similar under two temperature treatment in control (Fig 4.3a) condition whereas under combined stress condition (Fig 4.3b) photosynthesis rate in high temperature stress decrease sharply against small decrease in ambient temperature. Slight decrease in photosynthetic rate under high temperature and combined stress was also found in some cultivar (data not shown). Stomatal conductance follow the similar trend like photosynthesis under high temperature and combined stress (Fig 4.4) and under combined stress condition both decrease distinctly which is nearly 35-40% on average for whole season. According to these measurements, CO_2 concentration [CO_2] at high temperature was lower (270 µL/L) than ambient (281 µL/L) even more lower under combined stress (245 µL/L).

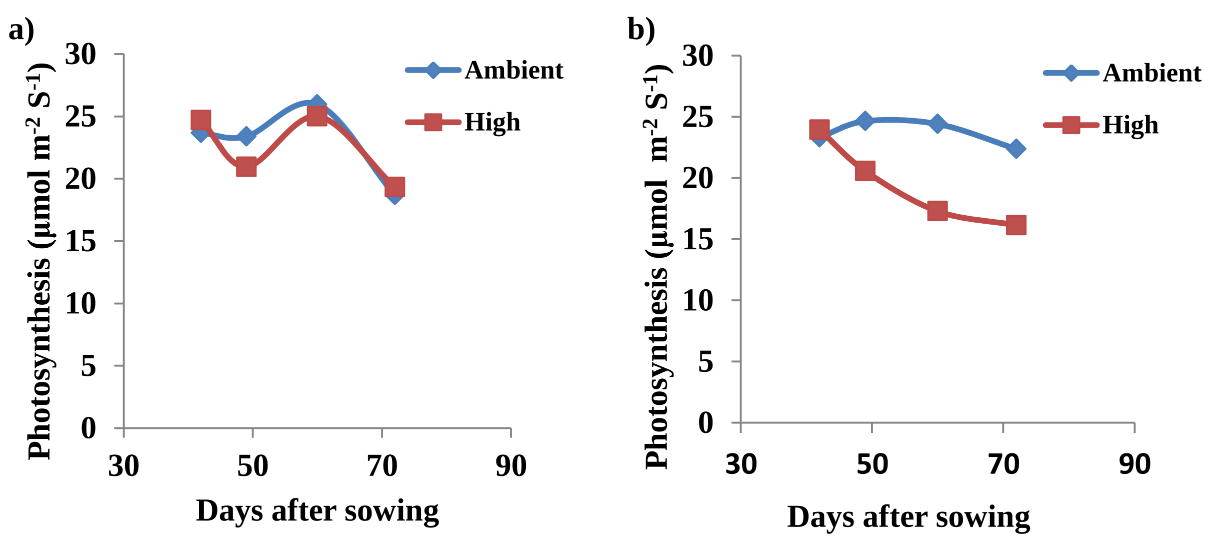


Fig. 4.3. Photosynthesis under (a) high temperature (b) high temperature and water stress condition in 4 soybean cultivar (2012).

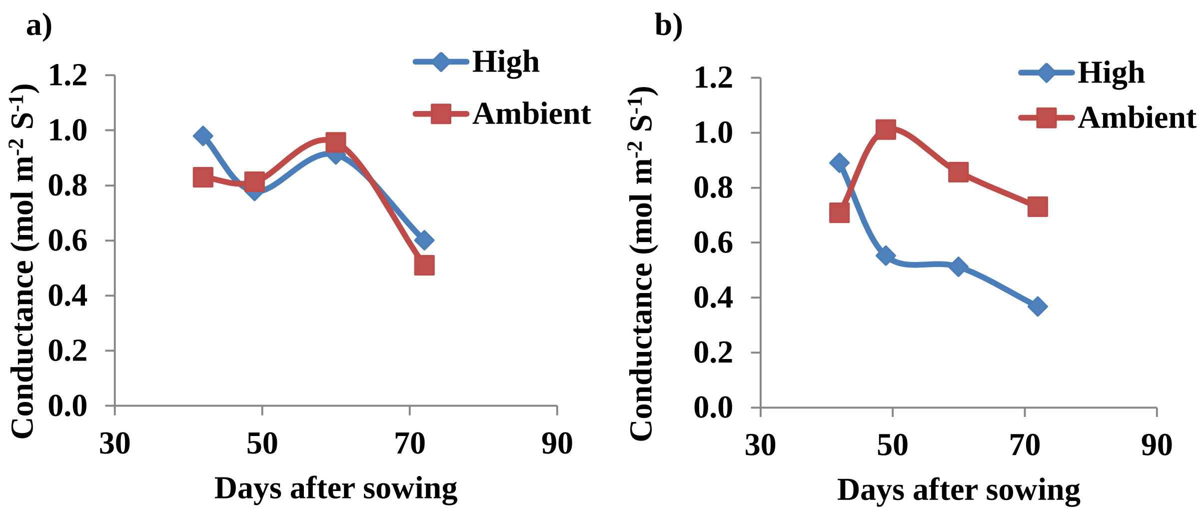


Fig. 4.4. Stomatal conductance under (a) high temperature (b) high temperature and water stress condition in 4 soybean cultivar (2012).

4.3.5 Carbon isotope discrimination (CID)

CID of Seeds showed that under high temperature and combined stress condition they reduced significantly in multiple cultivar and for single cultivar reduced under combined stress (Table 4.4). CID of leaves also showed similar significant reduction under Temperature stress (21.6‰ under ambient and 20.3‰ under high temperature).

Table 4.4 Carbon Isotope Discrimination ($\Delta^{13}C$) measured in seeds

Cultivar	Temp	Control	Drought
Stressland	ambient	20.42	19.84
	high	20.07	17.86
Enrei	ambient	20.39	19.86
	high	19.78	19.32
UA4805	ambient	20.18	18.93
	high	20.09	17.81
Futukuitaka	ambient	20.88	19.06
	high	20.48	19.06
ANOVA			
Temp(T)		<0.05	
Water(W)		<.001	
W X T		0.1	

4.4. Discussion

Increased temperature affects yields through different pathways. Shorter crop duration, which in most cases is associated with lower yields (Stone, 2001, Craufurud and wheeler, 2009) is one of them. In this study also Soybean phenology was changed under stress condition but duration was longer under stress. High temperature stress did not have significant effect on the onset of flowering (R1) stage but seed filling stage (R5-R7) was reduced by 2-3 days. Similar effect on phenology was observed under combined stress of high temperature and drought (Tacarindua et al., 2012). However, delayed onset of flowering by 1-3 day in some cultivar is also observed under combined stress condition. This can be related with the slowing of crop development rate under temperature stress (Hesketh et al., 1973; Jones et al., 2000) above optimum.

Reduction of photosynthetic rate was distinctly higher under combined stress than temperature stress alone (Fig 4.3, Fig 4.4) which is also observed in other combined stress studies (Xu and Zhou, 2006; Pradhan et al., 2012; Prasad et al., 2011). Temperature and drought stress accompanied with high VPD (Table 1) reduce the photosynthetic rate (Brandner and Salvucci, 2002) by causing partial stomatal closure (Bunce 1984; Fletcher et al., 2007) and decreasing flow of CO_2 into mesophyll tissue (Chaves et al., 2003) as observed during photosynthesis measurement and can be confirmed from the CID analysis of leaves. High temperature leads to an exponential increase in the VPD which leads to reduced water-use efficiency as indicated in the form of reduced CID (Table 4.4) which further increase canopy temperature ultimately may cause stomatal closure (Tacarindua et al., 2012; Ray et al., 2002). These stress condition also triggers delayed leaf senescence (Tacarindua et al., 2012) in TGC experiment which is an indication of sink limitation (Sinclair and De wit 1976; Egli, 2004) and this sink limitation is also reported by Liu et al. (2004) under drought condition.

Reduction of yield components (flower, pod, and seed) under stress condition can be correlated with the above mentioned alteration of physiological processes (Gibson and Mullen, 1996). Pod set ratio reduction was more pronounced under combined stress than high temperature stress alone in single and multiple cultivars (Xu and Zhou, 2006; Pradhan et al., 2012; Prasad et al., 2011). Reduction of podset ratio can be party contributed to the high rate of flower and pod abortion under stress condition (Djanaguiraman et al., 2013; Fang et al., 2010; Prasad et al.,, 1999; Yong et al., 2004) from failure to pollen germination (Fig 4.5) under stress condition. Pollen development during various phases of microsporogenesis is sensitive to high temperature

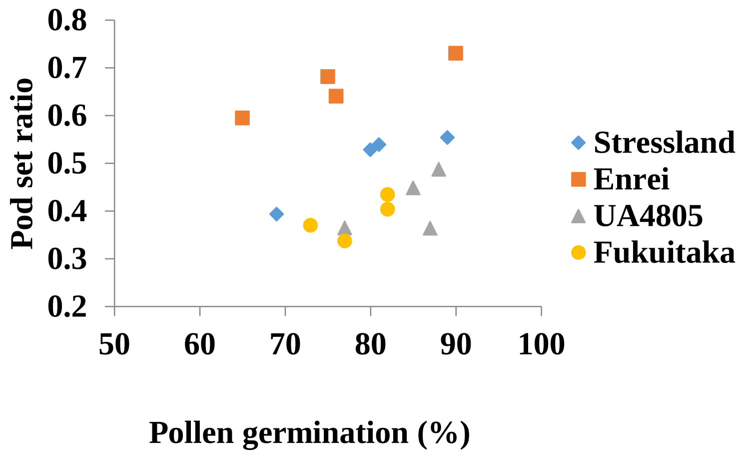


Fig.4.5. Influence of temperature and water stress on the relation between pollen germination and podset ratio (2012).

stress in soybean (Salem et al., 2007). The response of pollen germination toward combined stress was more severe than high temperature stress alone. Djanaguiraman et al. (2013) reported 23% reduction of soybean in vitro pollen germination under high temperature (38/28 to 28/18 ^{0}C) stress. Salem et al. (2007), Koti et al. (2005) also reported similar reduction in soybean pollen germination. Under stress condition pollen germination reduction to pod set ratio reduction is almost linearly related (Fig 4.5). This indicates that even a small increase as much as 2^{0}C of growing season temperature can reduce pollen germination about 6-15% across all cultivar and when this stress is coupled with drought it doubled to 25-30% resulting podset ratio reduction of 6-9% and 9-18%.

Seed yield is considered to be a function of seed number per area and seed size. Significant reduction of seed number has been found in all cultivar in both years under stress condition (Table 4.2, 4.3). A strong correlation between pollen germination and seed number as such with seed yield under stress condition (Fig 4.6) is observed in the study. Such type of strong relation has been also reported in groundnut (Prasad et al., 1999; 2000) and in bell pepper (Aloni et al., 2001), tomato (Sato et al., 2000). Chickpea (Devasirvathama et al., 2013; Fang et al., 2010) kidney bean (Prasad et al., 2002), sorghum (Prasad et al., 2006a; 2008a), and wheat (Prasad et al., 2008b; 2011) but all the studies either include high temperature or drought stress but not combined stress. Seed size reduction can be explained by the reduction of seed growth rate under high temperature (Tacarindua et al., 2012).

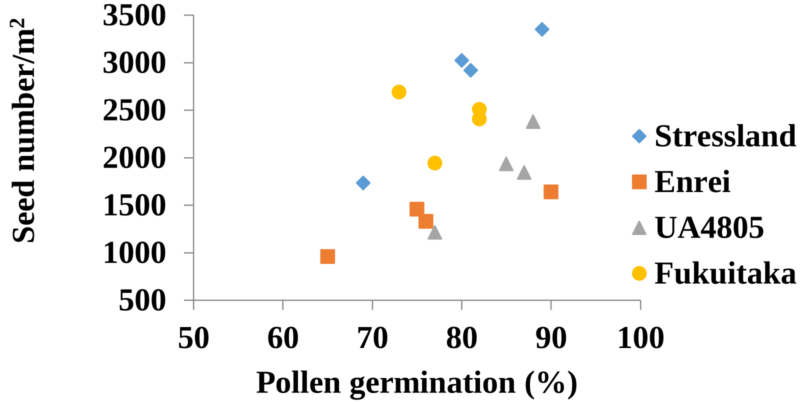


Fig 4.6. Influence of temperature and drought stress on the relation between pollen germination and seed number (2012).

The mechanism how high temperature, VPD and drought reduce pollen germination in soybean is not completely known. High temperatures cause poor anther dehiscence and reduce pollen release (Matsui and Omasa, 2002; Sato et al., 2002) which is also observed in this study. Heat stress can alter flower and pollen morphology (Djanaguiraman et al., 2013; Koti et al., 2005) like disintegration of the tapetum layer, increased exine wall thickness and condensation of chromatin etc. and thereby decreased pollen germination in soybean (Djanaguiraman et al., 2013). The direct effects of VPD on soybean pollen function are not known and require further investigation but study with maize pollen showed high VPD condition can reduce germination and viability (Luna et al., 2001; Aylor, 2004) very quickly.

In field like condition, concomitant effect of high temperature (ambient +2^{0}C) and water stress can reduce soybean yield up to 42% whereas high temperature alone can reduce 22% resulting from 28% to 11% pollen germination reduction. The effect of combined stress on physiological processes was more pronounced than temperature stress individually. However, more detail work is necessary to completely understand the mechanism of combined stress on soybean physiology.

Chapter 5

General discussion and conclusion

5.1. Soybean yield classification for Japan

Climate and crops are intimately related. Change in one drives change in another. To illustrate such relation between soybean yield and climatic factor variation this study was designed. This study analyzed the relation on the basis of statistical trend point of view with different geographical location and different time space.

In Chapter 2, Soybean yield pattern analysis for all the prefectures of Japan was carried out which revealed that soybean yield is influenced by regional pattern. 46 prefectures of Japan were classified into 9 group based on their homogeneity in yield variation from year to year. Each group formation showed distinct location specificity. PG1 consists of 8 prefectures from the northernmost and north-eastern part of the country while PG 8 consists of the 10 prefectures from the southernmost and southwestern part of the country. Thus north to south variation was prominent in the classification. This distribution also showed variability of yield was higher in the middle part of the country than northern and southern part. Yearly variation of yield was also categorized. The classification allows us to compare the yield in temporal and spatial scale. During the early period like YG1-YG4 (1948-1989) PG 6 comprised of 10 western prefectures showed consistently higher yield than other PGs but during the later period (1990-2012) yield became comparatively lower and showed negative trend. On the contrary, yield was relatively lower in the early period in PG1 (northern prefecture) and PG 8(southern prefectures) but became consistently higher than other PGs during the later period. This is a quite noticeable change in the yield pattern which may be related with regional climate change pattern.

5.2. Predictor variables for yield in Japan

I studied regional pattern of climate change next, to explain the variability of yield using the same spatial temporal scale and divided the whole time period into 2 according to the result of classification: period1 (1948-1989) and period 2 (1990-2012). Climatic parameters i. e. monthly average, maximum, minimum temperature, sunshine duration, precipitation showed remarkable seasonal pattern of change in both periods. Warming trend was clearly evident in all location from period1 to period 2. Seasonal variation in rise in average temperature was noticeable. Summer average temperature started to increase from later part of period 1while average temperature increase in autumn was prominent only from last 2decaeds.

Increase in monthly minimum temperature was higher than maximum temperature in almost all location. Maximum temperature of the summer months showed highest fluctuation in some location (PG 2, 4, 8). Increasing trend of monthly maximum temperature was evident much earlier in winter season than summer season while minimum temperature started increasing earlier in summer than winter. This implies that winter day compare to summer day started to become hotter in earlier period and summer night compare to winter night started to become hotter. These observations indicate that difference of day and night temperature is decreasing in all year round. This changing pattern of climate has the potential to affect yield positively and negatively depending on baseline temperature. Yield increase from period 1 to period 2 in the northern prefectures (PG1, 2) can be partly contributed to the increase in monthly average temperature while at the same time increase in temperature in middle to southern part (PG6) can be responsible for yield decrease as their baseline temperature is already near to optimum and beyond that yield responses negatively even if the increase is not high but coincides with reproductive stage can do severe damage.

Rainfall variation pattern was also seasonal. Summer rainfall was comparatively higher in period 1 than period 2. This decrease in rainfall was clearly evident in middle part (PG 4, 5, 6) of the country. Autumn rainfall showed an increasing trend in the northern PGs (PG1, 2). Monthly sunshine duration is also important factor that influence yield. A general reducing trend is observed for all the location. This sunshine duration is highly variable in winter season.

To quantify the relation between these factors and yield I performed multiple regression analysis considering all these factors. I found different relation in 2 different time period consisting with the climate change and yield variation. For example, in the northern area (PG1), the most important climate factor influencing yield was sunshine duration in July and June, average temperature of August and precipitation in September. Some of them had positive and some had negative correlation with yield and number of negatively correlated factors were higher than the positively correlated one in period 1 and vice versa in period 2. Such type of model was found for the 9 identified zones (PGs) which explained the variability of yield. Overall climate factors that are affecting yield positively is increase temperature of August, September and October (only for northern part, PG1). Factors affecting yield negatively are excess rainfall in Jun, July and September, October, increasing minimum temperature of September, October, Shorter daylight duration over the whole growing season.

5.3. Seasonal and periodic variability in solar radiation estimation model

Solar radiation can be estimated using different empirical model. I chose one of the most widely used and simple models and evaluated its applicability by using historical data in Japan for the purpose of regenerating historical solar radiation data. The model was proposed by Hargreaves and Samani (1982) and it is based on the relation between solar radiation (R_s) and daily temperature difference, extra-terrestrial radiation using an empirical coefficient, K_{RS} (0.16).

The Chapter provides sample evidence that Hargreaves-Samani model can be reliable but for better accuracy a seasonal pattern along with a periodic and location wise calibration may be necessary. The study was conducted using data of 10 different locations of Japan which showed distinct summer and winter variation. K_{RS} values were higher than original set value (0.16) in winter months and lower in summer months which created bias error with a seasonal pattern. The study also showed periodic increase in K_{RS} values for all location which was consistent throughout the whole year. Apart from seasonal and decadal bias the model also showed location bias with under estimation of solar radiation in the northern territory.

5.4. Predictor variables for soybean yield in Asia

Soybean yield and production variation in different countries in the world is a well known fact. In chapter 4, we tried to evaluate the yield variation in different countries of Asia with respect to climatic variability. 11 countries-India, Indonesia, Myanmar, Thailand, Vietnam, Turkey, Kazakhstan, Japan, China, North Korea, and South Korea in Asia on the basis of their contribution to the whole production were selected and yields with 2 leading producing countries in world-USA and Brazil were compared.

It was found that yield trend was positive in most countries and year to year fluctuation was not high in most selected countries except for Turkey which showed a dramatic increase in yield from the 1990s onward. Yield was comparatively higher in the upper latitude temperate countries like Turkey, Kazakhstan, Japan, China, north and South Korea and lower in tropical humid countries like India, Myanmar, Indonesia, Vietnam, and Thailand. But even the high yielding countries of Asia were way below the high yield of USA and Brazil. With time the lower yielding countries manage to improve yield little to minimize their gap with the higher yielding countries.

Relation between yield variation and climatic change was noticeable from the study. Climatic parameter like annual average, maximum, minimum temperature, precipitation and solar radiation was analyzed dividing in 3 time period: 1980s, 1990s, and 2000s in relation to yield change. Yield in 3 different time period was negatively related with average, maximum and minimum temperature when all the countries were considered; this correlation was higher when individual countries were considered where rise in annual temperature already exceeded the optimum level like India, Indonesia. Overall yield was reduced in Asia in 3 different time period due to rising temperature. Rainfall pattern in different countries showed different response as the total annual amount was highly variable among the countries. However excess annual precipitation over 1500 mm showed negative responses while below that showed positive response. The most obvious relation between temperature and yield was observed in the summer months. Solar radiation did not show any specific relation when compared with annual data but summer months solar radiation showed positive correlation with yield in almost all location. The study provides the evidence that summer maximum temperature and precipitation pattern of the recent years are common climatic factor that lowers yield in Asia in general.

5.5. Yield reduction from field experiment

Objective of this study was to correlate the results of statistical observation with field experiment in terms of Japan. Statistical study showed increasing temperature is one common negative factor influencing yield not only in Japan but also in Asia. As such the study was designed to quantify the effect of high temperature and water stress in TGC (Temperature gradient chamber) which mimics field condition. Two water treatments (control, drought) and 2 temperature treatments (ambient, high = ambient + 2°C) were imposed on 3 cultivars in 2011 (Enrei, Stressland, Tachinagaha) and 4 cultivars (Enrei, Stressland, Fukuitaka, UA 4805) in 2012. In vitro pollen germination was measured by collecting 10-15 flowers from 5 plants per treatment between 0800- 0900 h on the day of anthesis. Leaf photosynthesis and conductance were measured during flowering to pod set. At Maturity, 5 plants from each cultivar were used to calculate node number, pod number, seed size, seed number, seed yield and harvest index (HI). Pod set ratio was measured by counting the flower scar number and pod number at maturity.

Effect of temperature and water stress was statistically significant ($P<0.05$ to $P<0.01$) on pollen germination and all the yield components (flower number, pod number, podset ratio, seed number, single seed weight, yield). Cultivar difference was also significant in all yield components. Cultivar UA4805 and Fukuitaka were less affected by the stress condition than cultivar Tachinagaha and Enrei. Pollen germination, pod set ratio and seed yield reduction under high temperature and combined high temperature and water stress across all cultivar on average were 11% – 28%, 8% – 18% and 22% – 42% respectively. Seed number and Pod set ratio under stress condition was linearly correlated with pollen germination. Almost all the yield components (flower, pod, and seed) were reduced under combined stress and under high temperature stress condition while longer crop duration was observed under all stress condition.

5.6. Future yield prediction

Our study shows that in this 21st century climate change pattern can be a cause of soybean yield reduction. Historical trend analysis for Japan and major soybean producing countries suggests that yield is already suffering due to lack of rainfall (drought) and sometimes excess rainfall (flood) during the growing season. This dreadful impact of drought and flood has been already identified and investigated by several researchers (Ries et al., 2012, Fenta et al., 2011; Yordanov et al., 2000). However the impact of high temperature stress on soybean yield is not as unanimous as drought and flood but in our study we found that annual average temperature is increasing alarmingly and yield is decreasing correspondingly. If this trend continues which is most likely soybean yield will reduce not only in hot tropical countries but also in the cold temperate countries which is in agreement with some other studies. Even benefits from doubling of CO_2 will not be enough to counteract the yield reduction in some regions (Lal et al., 1999). Moreover, there is a positive correlation between the increasing trend of average monthly temperature and extreme temperature event like short spell of heat stress (Griffths et al., 2005) which will also reduce the yield. Our study also shows that increase in minimum temperature is higher than maximum temperature which in term indicates that increasing night temperature also can be an issue for soybean yield which has been found in some other crops (Izquierdo et al., 2002; Loka and Oosterhuis, 2010; Mohammed and Tarpley, 2009). Our study also shows the tendency of decrease in day length which is correlated with yield reduction and this sensitivity to day length has been found in many studies, too (Kantolic and Slafer, 2005).

Our field experiment with increasing growing season temperature (2-4^{0}C) in combination with moderate drought shows that yield reduction can range from 16-50% by decreasing pod set ratio (2-33%) which is in agreement with other research relating yield and high temperature stress (Tacarindua et al., 2012; Ferris et al., 1999; Gibson and Mullen 1996).

5.7. Conclusion

Finally it can be said if present rate of global warming continues which is expected in future climate projection scenarios soybean yield will reduce not only due to the extreme climate event and changes in precipitation pattern, but also from high temperature stress. This statistical study in conjunction with field experiment shows the significance of high temperature stress on hampering soybean yield in regional as well as global scale. The study reveals that regional adaptation to agronomical practice along with breeding strategy for resistant cultivar should be given prime importance in order to improve yield.

Acknowledgement

This thesis was completed after the study for four years at the Laboratory of crop science, Graduate School of agriculture, Kyoto University. I want to express my deepest sense of gratitude to the almighty God that made me successful to complete this thesis. I sincerely like to thank all the people who help me to complete this study.

First of all, I like to express my deepest, heartiest gratitude to Prof. Tatsuhiko Shiraiwa for his guidance, valuable advice, useful comments, meticulous reading, and extensive help throughout the whole study period and to Dr. Koki Homma for his continuous supervision, relentless support and unequalled patience to teach me.

I like to extend my gratitude to Dr. Tomoyuki Katsube-Tanaka and Dr. Yu Tanaka for their valuable advice and comments on the research. I would also like to thank Dr. Yasuko Fukuda for her help and advice in laboratory analysis as well as in field.

I would like to thank all members of Laboratory of crop science, especially Dr. Custodio R.P. Tacarindua, Mr. Keiichiro Nakashima, Mr. Kenichiro Fujii, Mr. Yohei Kawasaki, Mr. Mochamad Arief Soleh, and Mr. Akinori Yoshifuji for their help in the field.

Finally, I am grateful to my mom and my younger brother- Mr. Saddam Hossain for their support and encouragements as well as my friends and well wishers in Japan and Bangladesh.

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*** In Japanese with English abstract.**

**** In Japanese.**

List of symbols and abbreviations

symbol/abbreviation	description	unit
CID	Carbon isotope discrimination	
DOY	Days of year	
HI	Harvest index	
K_{Rs}	Empirical coefficient	
P1	Period 1 (1948-1989)	
P2	Period 2 (1990-2012)	
PG	Prefecture group	
Ppt	Monthly precipitation	mm
R_a	Extra terrestrial radiation	$MJ\ m^{-2}$
R_s	Solar radiation	$MJ\ m^{-2}$
R1	Beginning of flowering	
R5	Beginning of seed filling	
RMSE	Root mean square error	
Sd	Monthly sunshine duration	hr
Tav	Average monthly temperature	^{o}C
TGC	Temperature gradient chamber	
Tmax	Maximum monthly temperature	^{o}C
Tmin	Minimum monthly temperature	^{o}C
T_t	Transmissivity coefficient	
VPD	Vapor pressure deficit	kpa
YG	Year group	
YP1	Yield in period 1	
YP2	Yield in period 2	

List of publications

(Chapter 3)

Hossain S, Homma K, Shiraiwa T, 2014. Decadal and monthly change of an empirical coefficient in the relation between solar radiation and the daily range of temperature in Japan: implications for the estimation of solar radiation based on temperature. *Plant Prod Sci*. vol. 17(in press)

(Chapter 3)

Hossain S, Homma K, Shiraiwa T. Influence of climate factors on soybean yield in Asia. *Plant Prod Sci*. (under submission).

(Chapter 4)

Hossain S, Homma K, Shiraiwa T. Independent and combined effects of high temperature and water stress on soybean yield, podset, and pollen germination in temperature gradient chamber. *Plant Prod Sci.* (under submission).