Differences in rice production in Asia, with a focus on cropping intensity

Student: Soma Forgács 7070128
Supervisor: Kees Klein Goldewijk
Second reader: Kevin Mganga
Submission date: 2023/06/29
Wordcount: 6289

Rice crop at Yenda, near Griffith, NSW. 2000. by CSIRO

Contents

Summary

This paper explores the differences in agriculture in Asia through multiple cropping, which is sowing and harvesting from the same piece of land multiple times a year (Dalrymple, 1971). The focus will be on rice, the staple food for about half the global population. Rice is even more important in Asia as it is the staple food for around 90% of people (Fukagawa & Ziska, 2019). The population of Asia will grow by 300 million people (United Nations, 2022b), but the continent already has the highest number of people suffering from malnutrition (FAO et al., 2022). It is unknown if intensification could reduce this number as few land use models include multiple cropping in their calculations, which could impact their accuracy. HYDE is one of the few models to include multiple cropping, dating back to 10,000 BC (Goldewijk et al., 2017). These numbers for multiple cropping are based on a limited number of studies, and for countries without data it is taken from its neighbours. This paper calculated the Multiple Cropping Index (MCI) from the literature on land use, this is a term that indicates the average number of harvests every year. This was used to answer the question: how does multiple cropping differ in countries in Asia, how can these differences be explained, and how can they be applied to land cover databases? A literature search yielded 70 results which were used to calculate the MCI for 16 Asian countries. These MCI were then compared with the one used by HYDE, which showed that HYDE overestimated the effects of multiple cropping for all countries until around the 1950s. It also overestimated the MCI for some countries after this date, but the literature is uncertain, and many sources disagree. There is a need for research to decide how multiple cropping should be measured.

Introduction

Asia and food security

Asia (figure 1) is the most populous continent with around 4.75 billion people, more than half of the global population of 8 billion (United Nations, 2022b; United Nations Department of Economic and Social Affairs, Population Division, 2021). The global population is expected to rise to 10 billion by 2080 (United Nations, 2022b), and the population of Asia will increase by about 500 million. The population in East Asia will drop by around 500 million while South and Southeast Asia will grow by around 600 million and 100 million respectively (Appendix A). This means that there will be around 300 million new mouths to feed in these three regions. Asia as a continent already has the highest number of people suffering from malnutrition, 425 million out of the 768 million people that suffer from it globally (FAO et al., 2022). Rice is the staple crop in Asia, and it is unclear if the growth in demand can be met by increasing intensification in Asia (Canisius et al. 2007) while imports of food are already double that of exports (FAO, 2021).

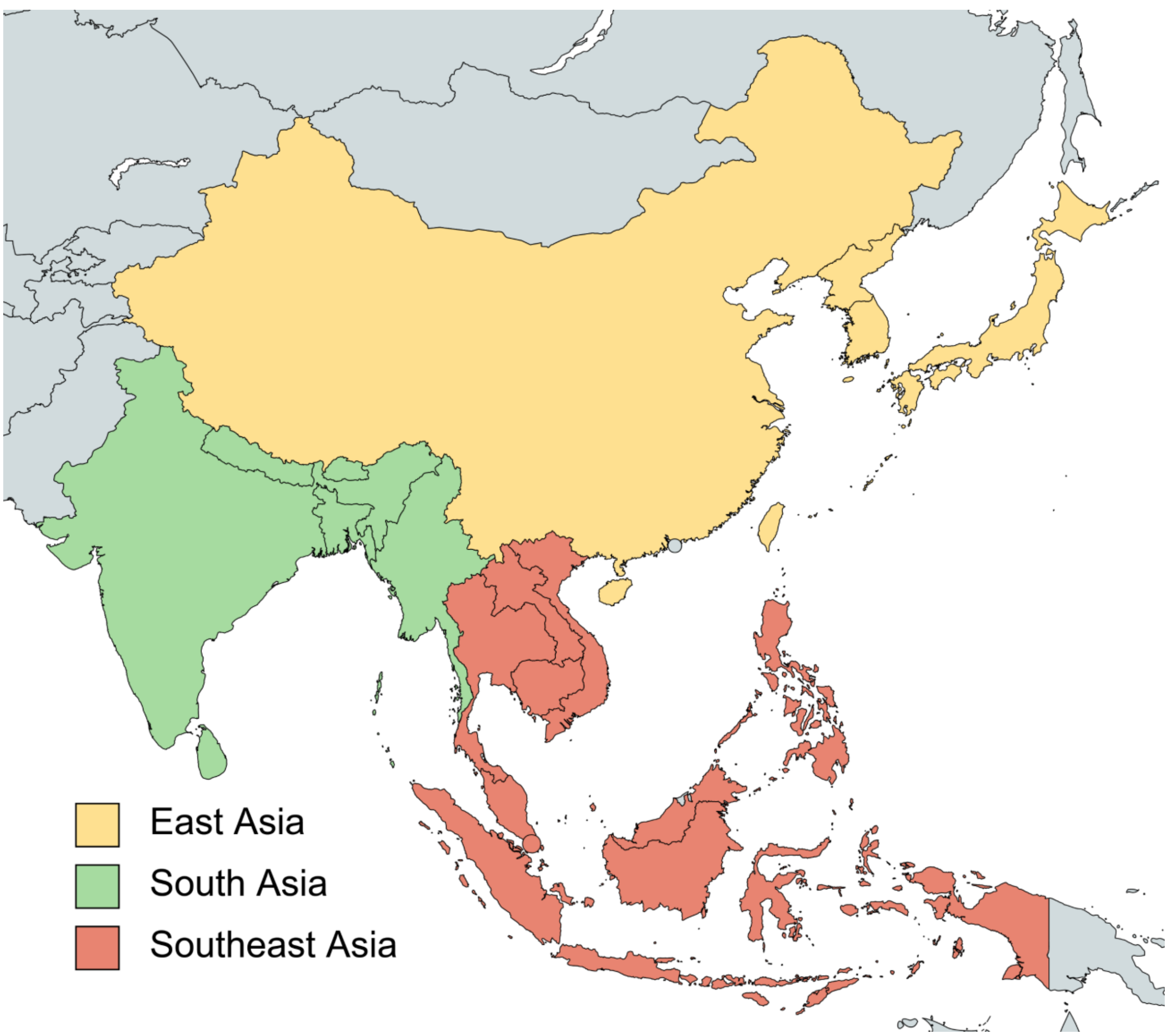

Figure 1. Map of the Asian countries part of this paper. The colours of the countries correspond to their regions: yellow is East Asia, green is Southern Asia, and red is Southeast Asia. These countries were chosen because rice is common in these areas.

Rice

Rice is a staple food for around half of the global population, with around 90% being consumed in Asia (Fukagawa & Ziska, 2019). Rice originates from Asia, having been found in archaeological sites dating back to 8,000 BC, it is still debated when it was first domesticated (Sweeney & McCouch, 2007), but by 2,000 BC it was already domesticated and used in agriculture (Sweeney & McCouch, 2007). There were many different types of rice, and they were selectively bred for faster growth, higher yields, and disease and pest resistance (Ho, 1956).

While rice can be grown in fields it is usually grown in paddies, where rice is flooded for most or all of the growing season. This protects the rice which can survive in flooded environments from weeds and pests which find it more difficult. These paddies can either be rainfed or irrigated, with tropical regions being able to support rainfed paddies year-round. Rice can also be harvested multiple times a year, as it matures in only four to six months (Brouwer et al., 1989). This means that rice is an important food crop, especially in the tropical regions of Asia.

Cropping intensity

When multiple crops are harvested in a year in one region it is referred to as multiple cropping, while the number of harvests in a year is called the cropping intensity. Equatorial regions with high rainfall tend to have higher cropping intensities as the abundant sunlight and rainfall allow for year-round growing of crops and multiple planting seasons. The conditions in East, Southeast, and South Asia are therefore well suited to multiple cropping. 73% of the global multiple cropping takes place in Asia, and 63% of this takes place in irrigated areas (Waha et al., 2020).

Some food crops are also more often used in multiple cropping, 34% of rice is double or triple cropped while only 10% of maize is for example (Waha et al., 2020). It is also important to note what crop they are planted with, in China rice is often cropped with itself but other combinations such as with alfalfa, rapeseed, or wheat are also possible (Frolking et al., 2002). Wheat on the other hand is more commonly cropped with maize there (Frolking et al., 2002). Of note is that close to half of all multiple cropping involves rice (Waha et al., 2020). Paddy rice experiences an even higher degree of multiple cropping, close to double that of normal rice (Waha et al., 2020).

Multiple cropping is not a recent phenomenon, Martello (2022) and Rita et al. (2021) both argue that multiple cropping has been around since at least the late first century BC. That does not mean however that it was already widespread in the past, Perkins (2017) claims that rice double cropping was common but not substantial in the Ming era in China (1368-1644).

Research gap

There are many unknowns when looking into multiple cropping, as many countries do not have definitive statistics on it. The statistical database FAOSTAT published by the Food and Agriculture Organization (FAO) of the United Nations is the most comprehensive global statistical database on agriculture but does not include multiple cropping. Most country databases do not include multiple cropping either, while historical data on the extent of multiple cropping is limited (Dalrymple, 1971).

It is unknown if multiple cropping can keep expanding to keep up with the growing populations or how climate change might impact agriculture in Asia (Canisius et al. 2007). There are limits to the effectiveness of additional irrigation, fertilizer use, increased agricultural areas, and increased multiple cropping (Canisius et al. 2007). There are also environmental considerations for each of these approaches, such as nutrient runoff, water scarcity, or habitat loss. Rice when grown in paddies releases potent greenhouses gasses (AgLEDx Resource Platform, 2022; Zhang et al., 2011), but it is unknown if the increasing temperatures are beneficial or damaging to rice growth (Soora et al., 2013; Yao et al., 2007).

HYDE

One of the most comprehensive global databases for historical land use is the History Database of the Global Environment (HYDE) by Goldewijk et al. (2017) which goes back to 10 000 BCE. There is however a large uncertainty in the data produced by hindcasting based on data from 1900-2000 to available data for the year 1000. Hyde incorporates cropping intensity, but the intensities are based on only 4 sources (Goldewijk, personal communication May 17, 2023). These are Frolking et al. (2002) for China, Ara et al. (2016) and Timsina and Guilpart (n.d.) for Bangladesh, and (India - Global Yield Gap Atlas, n.d.) for India. Averages of neighbouring countries are taken for the other Asian countries as they are likely to have similar intensities.

Research question

This project will therefore examine the cropping intensities used by HYDE and compare it with the literature on multiple cropping in Asia. This will be done to evaluate if different intensities or changing intensities could be used to increase the accuracy of the land cover changes. If the intensities in the literature are found to be different, then the cause of these differences will be examined, and new intensities based on this information will be formulated. Therefore, the research question will be: how does multiple cropping differ in countries in Asia, how can these differences be explained, and how can they be applied to land cover databases? The relevant countries and their regions can be seen in Figure 1.

Theory and concepts

Research into multiple cropping is a recent development and sources still disagree on the precise definitions of terms that are used. This chapter will attempt to explain all the key concepts and the different terms that are found in the literature and how they interact with each other.

Multiple cropping and cropping index

Multiple cropping is when a piece of land is sown multiple times a year and is common in tropical areas and Asia in particular (Waha et al., 2020). Multiple cropping is usually divided into double and triple cropping which is when land is sown two or three times in a year respectively. The average amount of harvests in a year in one region or country is called the *multiple cropping index* (MCI) (figure 2), which is either a number between 1 and 3, or a percentage from 100% to 300%. For example, Zuo et al. (2014) calculated that the MCI in China in 1995 was 158%, this means that the 58% of the agricultural was used multiple times.

The MCI is also referred to as cropping intensity (e.g., in Waha et al., 2020), cropping frequency (e.g., in Estel et al., 2016), or harvest frequency (e.g., in Ray & Foley, 2013). Cropping frequency and harvest frequency refer to how often a farmer sows or harvests their land respectively. While cropping intensity has the same definition as MCI. Cropping intensity can however refer to fertilizer use, mechanization, and intensive agriculture. This paper will use MCI as that is what the Food and Agriculture Organization of the United Nations uses in their reports and because it is less often confused with other terms in the literature.

Harvested and physical area

MCI can be calculated by dividing the harvested area by the physical area (Waha et al., 2020) (figure 2). The physical area is the total cropland in a region usually in million hectares (Mha) or hectares (ha) and is only counted once, harvested area (in Mha or ha) on the other hand is counted as often as it is cropped. So, if a country has 2000 Mha of cropland and 500 Mha is double cropped then the harvested area would be 2500 Mha. Harvested area is also referred to as sown area (e.g., in Frolking et al., 2006) or planted area (e.g., in Sakamoto et al., 2009) in the literature, the harvested area will be used as harvests can be missed due to natural disasters, pests, or other disruptive events. Physical area is also called land area (e.g., in Frolking et al., 2006), agricultural area (e.g., in Langeveld et al., 2014), cultivated land (e.g., in Lin & Ho, 2003), or cropland area (e.g., in Yu et al., 2018) in the literature.

Some sources do not report harvested areas separately from physical areas, but these can still be used if production (in tons t) and yield (in tons per hectare t/ha) are included (figure 2). The production divided by the yield gives the number of hectares that were harvested (in ha). This can then be used to calculate the MCI. The MCI can also be calculated if the share of single, double, and triple cropping (e.g., in Xiang et al., 2019) (landcover share) is included (figure 2). If an area has 80% single, 15% double, and 5% triple cropping then the MCI will be 80% + 15% * 2+ 5% * 3 = 125%.

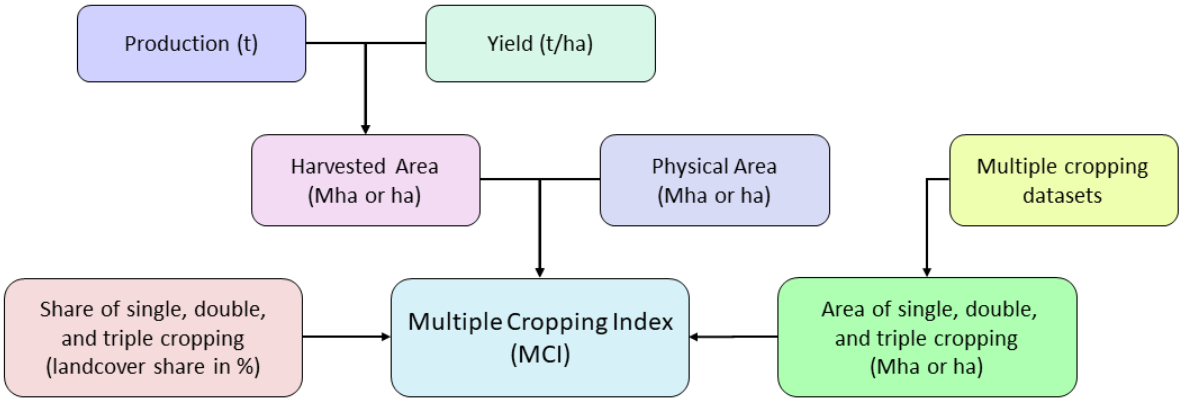

Figure 2. Illustrated conceptual framework with the ways to calculate the MCI using different types of data and the way that these data relate to each other.

Multiple cropping (paddy) rice

HYDE only includes multiple cropping for rice, and this is then limited to Asia (Goldewijk, personal communication May 17, 2023), but multiple cropping involves many crops in different combinations that depend on the region (J. Qiu et al., 2003; Yan et al., 2014). Additionally, rice is more often double, and triple cropped than other grains (Waha et al., 2020), and this is even more common for paddy rice (Frolking et al., 2006; Waha et al., 2020). Both rainfed and irrigated paddy (wet) rice have an MCI that is double than that of upland (dry) rice (Waha et al., 2020). Few sources report the MCI per crop, so only the MCI for all crops can be used. Therefore, care must be taken when taking MCI from sources to not underestimate the MCI for rice.

Multiple cropping datasets

Some sources such as Han et al. (2022) and Waha et al. (2020) include datasets in the form of maps with MCI included. These datasets are created with the help of satellite imagery and census data, and when used with mapping programs such as ArcGIS they can also show single, double, and triple cropping extents. These can then be used in the same way as the landcover share to calculate the MCI (figure 2). These datasets also come with metrics for accuracy such as the producer's and user's accuracy, for us the user's accuracy is important as it shows how likely it is that a classification on the map will be present in real life (Humbolt State University, 2019).

Methods

Literature search

A preliminary literature search was conducted to find relevant keywords to use to search for relevant literature. Waha et al. (2020) had a good overview of many different multiple cropping studies and an excellent reference list that led to the sources that formed the baseline for this research. This led to many different keywords that could be used, but the reference list for each study proved to be much more helpful. Research into multiple cropping is a relatively recent development and many sources referenced earlier research papers. This proved to be limiting as many sources only referenced papers from the same country, therefore a literature search with keywords was still conducted.

The keywords that were used in the literature search were "multiple cropping", "cropping intensity", "cropping index", and "harvest frequency", these were then combined with "Asia" or the country names for the countries in figure 1 and "rice". The search was executed in Scopus and the search totalled 394 results, when the duplicates were removed this decreased to 304 results. This was narrowed down to 34 search results that were related to calculating or mapping the MCI in a region or country. Additionally, a directed search was done to find the earliest point when multiple cropping became widespread which could be used as a starting point from which the MCI would increase. This was because HYDE had a linear increase of MCI from the year 10,000 BC until the present day.

These sources were then combined with data from regional governments and NGO websites for a total of 70 sources on the MCI or data to calculate it for Asian countries. Most sources focused on a single country or some regions in one country, while a few had two or more countries or the entire continent.

Computing the MCI

Some sources had calculated the MCI or its equivalent already, but for the others the MCI had to be calculated, read from graphs, or read from total map coverage. The MCI could be calculated in three separate ways from three different kinds of data: from the area under multiple cropping, the share of each kind of cropping (single, double, triple) in percentages, and from the harvested area and physical area in hectares (figure 2). This is straightforward for the area and the share under multiple cropping as they are the same data visualized in separate ways. The share is calculated from the area by dividing the area under one kind of cropping by the total:

$$Share\ of\ single\ cropping\ (\%) = \frac{Area\ under\ single\ cropping\ (ha)}{total\ area\ (ha)}$$

This can then also be done with double and triple cropping to get the share for each one. These shares can then be used to calculate the MCI:

$$MCI\ (\%) = Share\ of\ single\ cropping\ (\%) * 1 + share\ of\ double\ cropping\ (\%) * 2 + share\ of\ triple\ cropping\ (\%) * 3$$

Where each kind of cropping is counted the number of times that it is cropped. If the harvested area and physical area are provided by the source, then the MCI can be calculated by dividing the two:

$$MCI\ (\%) = \frac{Harvested\ Area\ (ha)}{Physical\ Area\ (ha)} * 100\%$$

Some sources do not provide the harvested area and only give the yield (in tons per hectare t/ha) and total production (in tons t), in which case this formula will be used instead:

$$Harvested\ Area\ (ha) = \frac{Total\ Production\ (t)}{Yield\ (t/ha)}$$

From this, the MCI can then be calculated using the previous formula for MCI (%). These formulas for calculating the MCI are based on those used by Dalrymple (1971) and the calculations were conducted in Excel.

Interpolation

This still leaves large gaps between the data points; these could be interpolated from the data before and after or by following a trendline. Qiu et al. (2017) show that there can be large year-by-year variations in MCI, but that there can be trends seen within them. Data will be interpolated, when possible, but if a trend can be detected based on the data for a certain period, then that will be used to create a trendline instead.

Limited data

Some countries do not have as much research on multiple cropping available as others. China, India, and Bangladesh had an abundance of sources to use, but countries such as Bhutan, Japan, and Sri Lanka had few or none. In these cases, the MCI of neighbouring countries has to be taken to fill in this gap. This has to be done on a case-by-case basis, as some neighbouring countries can have very different MCIs. This is caused by different environmental situations and topographies, such as Viet Nam having the fertile Mekong Delta or Nepal having a high average altitude where rice grows poorly. Additionally, not all countries had up-to-date information on their MCIs. Either there has not been any research in recent years, or studies work with older statistical data.

Comparison with HYDE

The MCIs that were calculated and taken from the sources were then compared with that of HYDE (Goldewijk et al., 2017) and the land use maps were also explored. If HYDE predicts the correct land use for locations with the MCI that it has now then it might not be the best idea to complicate it further, and if regional differences could be shown with other parameters such as soil suitability and climate such as those used in HYDE to predict cropland distribution (Goldewijk et al., 2017) then that might be preferable.

Results

Earliest point of double cropping

HYDE sets the MCI to 1 in the year 10,000 BC (figure 3) and interpolates it to the year 2020 (Goldewijk, personal communication May 17, 2023). According to Rita et al. (2021) and Martello (2022), multiple cropping may have been present by 3,000 BC but did not involve cropping rice with itself. Ho (1956) argues that double cropping of rice became possible between the years 1012-1174 based on the evolution of the meaning of the Chinese word for Hsien rice, a fast-growing rice variety that enabled double cropping. This rice type was imported in 1012 from Indochina (modern-day Viet Nam, Laos, Cambodia, Thailand, and peninsular Malaysia) and after 162 years, it became known as fast-growing rice.

This sets the earliest date that the MCI could rise from in China, other countries either adopted multiple cropping from China or developed it independently. Greenland (1997) states that this could be the case with India where it could have developed independently with advanced irrigation methods, citing a 14th-century writer called Ibn Battuta. Furthermore, Perkins (2017) says that rice double cropping was common but not substantial yet in the Ming era (1368-1644) in China, and the sources found for most countries indicate an extreme increase in MCI starting around the 1960s with the second green revolution (Rahman, 2010). Figure 3 shows the MCI used in HYDE, and the MCI starts rising from 10,000 BC already. Figure 4 shows the HYDE estimate compared to measurements from a paper by Zuo et al. (2014) with the starting date for the increase set to 1700.

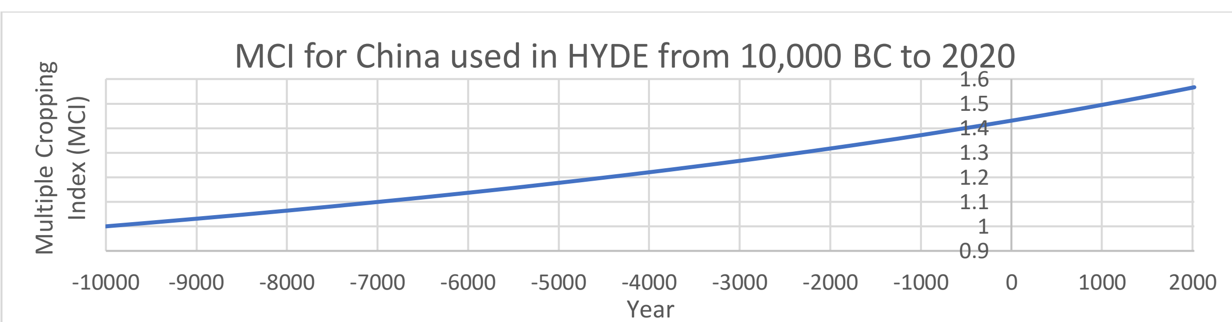

Figure 3. The MCI graph for China that is used in HYDE, the date starts at 10,000 BC and ends in 2020.

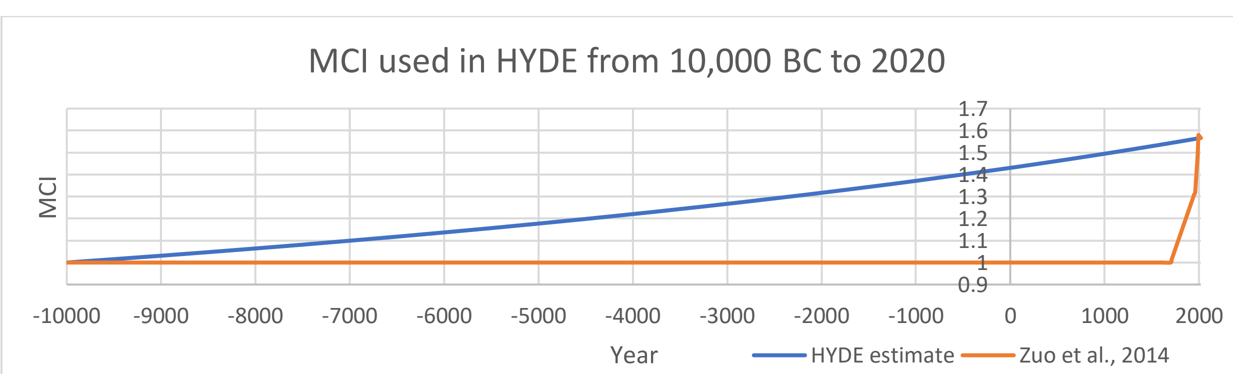

Figure 4. The MCI graph for China by HYDE and by Zuo et al. (2014), showing the large disparity between the two. HYDE works with 100-year intervals between the years 0 and 1700 and with a 10-year interval between 1700 and 1960, the same intervals were used to create the second line, which is why it seems to jump in steps.

Bangladesh

Bangladesh is one of the most intensively farmed countries in the world, and food security was important to the government after the country broke away from India and Pakistan. Figure 5 shows the development in the MCI for Bangladesh, it started low at only 1.3 but increased over time to over 1.9. Sources mostly agree on the slow but steady increase in MCI. Figure 6 shows this calculated MCI compared with that used in HYDE, the HYDE MCI starts higher (1.5) and increases in two steps, the similarities from 1999 to 2007 are because data from Ara et al. (2016) was used in HYDE and these calculations.

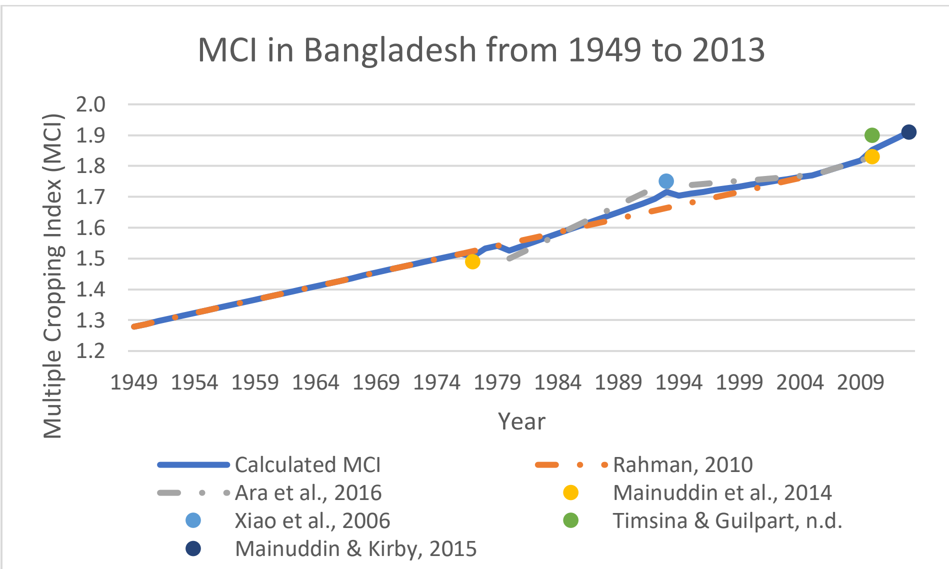

Figure 5. The MCI graph for Bangladesh from 1949 to 2013, showing an increase in MCI from 1949 to 2013. The dashed lines show studies with multiple years of data, while the dots represent single year datapoints.

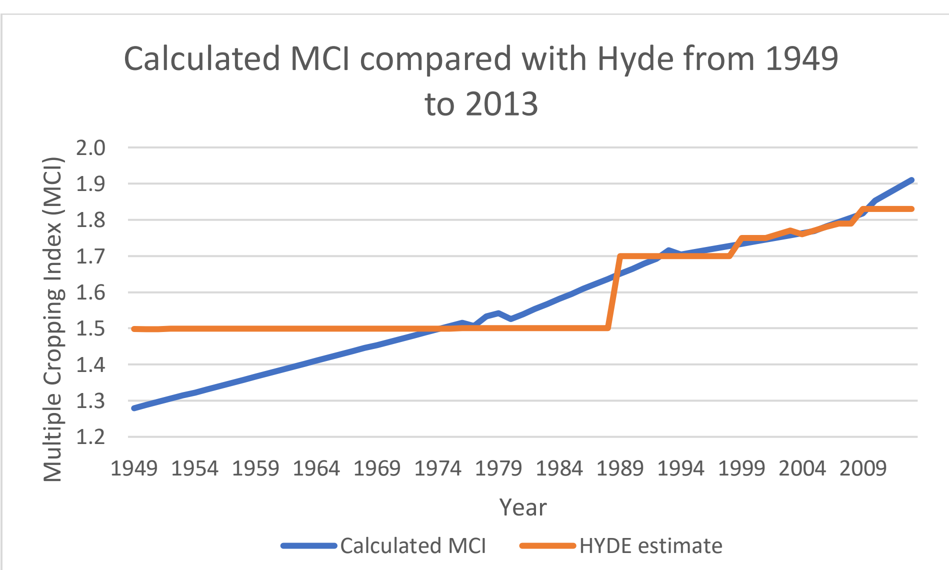

Figure 6. The calculated MCI from figure 5 compared with the MCI used in HYDE from 1949 to 2013.

India

Figure 7 shows the MCI in India from 1973 to 2010, unlike with Bangladesh the data does not go as far back. Wahiduddin et al. (1994) have information for all crops and only rice, but these do not line up with those used by Biradar and Xiao (2011) which predict a smaller increase than is found by Frolking et al. (2006). Frolking et al. (2006) and Xiao et al. (2006) disagree in the years 1999 and 2000, but this could be explained by an unexpectedly good or bad year for multiple cropping. Biradar and Xiao (2011) have a higher MCI than Gumma et al. (2016) which might imply a decrease in MCI, but this might also be explained by Gumma et al. combining data for Sri Lanka and India which could influence the average. Figure 8 shows the calculated MCI compared with that used by HYDE, there is a small difference until the jump in MCI from Biradar and Xiao (2011).

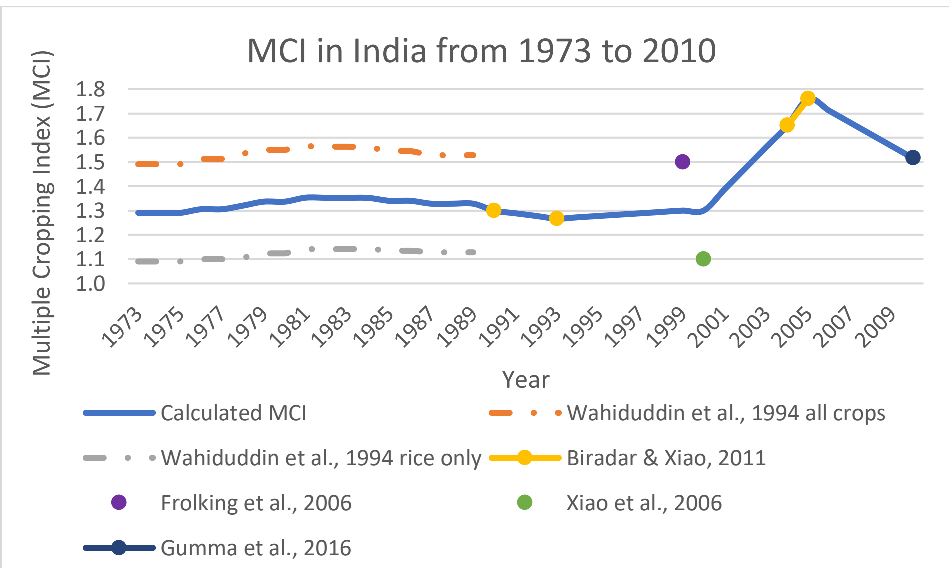

Figure 7. The MCI graph for India showing the progression of MCI from 1973 to 2010. (data by Biradar & Xiao, 2011; Frolking et al., 2006; Gumma et al., 2016; Wahiduddin et al., 1994; Xiao et al., 2006)

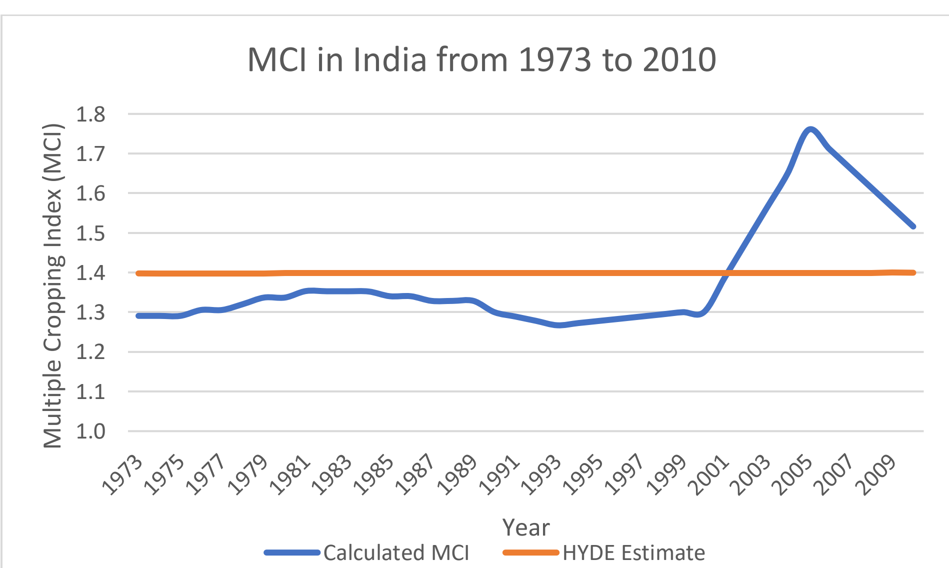

Figure 8. the calculated MCI from Figure 7 compared with the MCI used in HYDE from 1973 to 2010.

Sri Lanka

Sri Lanka is close to India but there is not much information available on the MCI there, but it will likely be like that of India. Xiao et al., 2006, and Gumma et al., 2016 put the MCI of Sri Lanka around 1.5 for the years between 2002 and 2010. There is no mention of any large-scale increases in MCI around these years and no literature on the effects of the second green revolution (Rahman, 2010) here. The MCI for Sri Lanka likely rose after the 1950s and stayed stable like that of India between the 1970s and 2020. HYDE uses the same MCI as it does for China, which is close to the calculated MCI and the differences can be explained by year-by-year differences.

China

China has a long history of multiple cropping, and it was expected that the MCI would be high, but sources seem to disagree with this (figure 9 & 10). Figure 9 shows the original calculated MCI, while Figure 10 shows a smoothed line. The smoothed line shows the increase and decrease in MCI better, while yearly variations can heavily influence the MCI so in my opinion it is as accurate as the non-smoothed one. Data from before 1980 are not readily available as no statistics were released by the Chinese government before then, additionally, only the cropland losses have been included in official statistics (J. Qiu et al., 2003).

This means that the MCI is a bit distorted in any sources that rely on the official statistics and do not choose to try and adjust for it. The only thing that sources can agree on is that in 1995-1996 the MCI was between 1.5 and 1.6 (B. Qiu et al., 2017; J. Qiu et al., 2003; Siebert et al., 2010; Yan et al., 2014; Q. Yu et al., 2018; Zuo et al., 2013) and that until then there was an increase and afterwards a decrease. The decrease was caused by urban development taking over agricultural land with high MCI and being replaced by lower-quality soils in the north and west (B. Qiu et al., 2017).

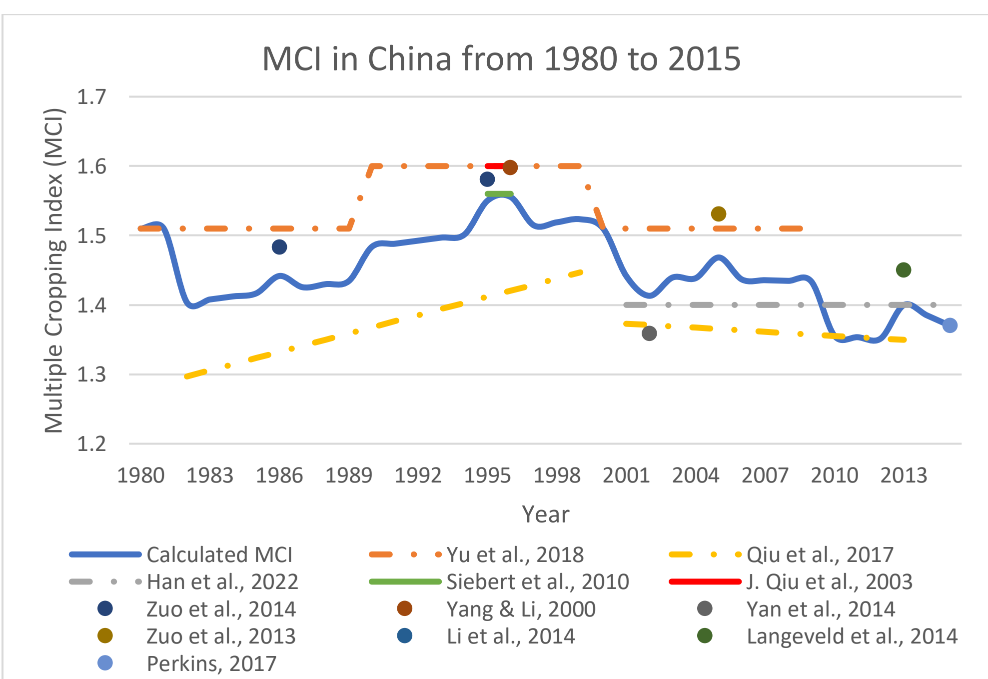

Figure 9. the MCI graph for China, showing a lot of variation in MCI from 1980 to 2015.

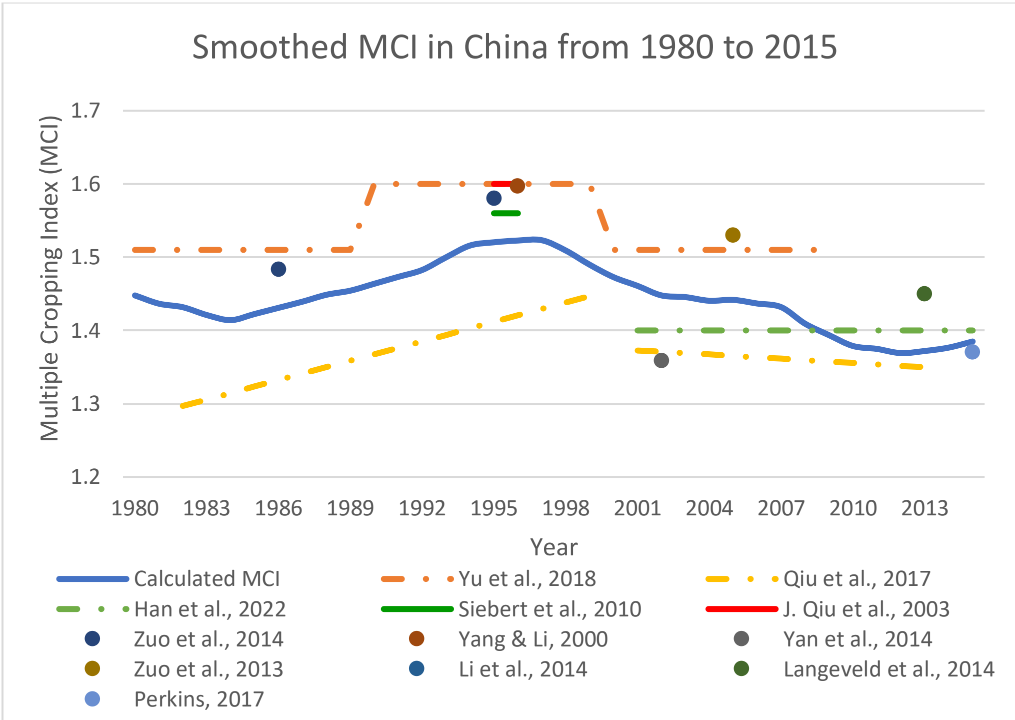

Figure 10. the MCI graph for China from figure 9, with a 5-year smoothing filter applied to see long term variations more easily.

This calculated MCI is then compared with the one used in HYDE in Figure 11. This shows that the one used by HYDE overestimates the MCI while not showing the increase/decrease before and after 1996.

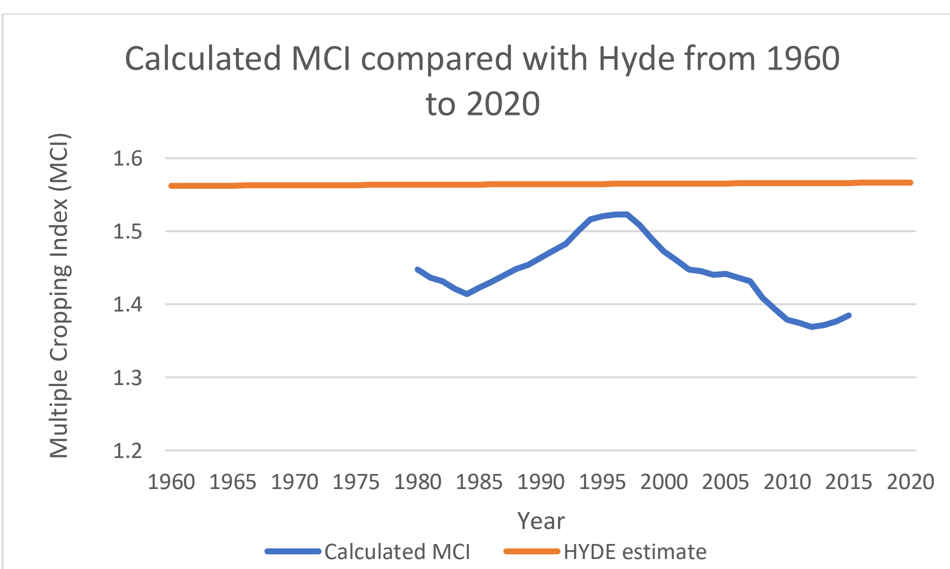

Figure 11. the calculated MCI from Figure 10 compared with the MCI used in HYDE from 1960 to 2020. The MCI used by HYDE is higher than what was calculated and does not show a decrease after 1996.

Viet Nam

Rahman (2010) argues that there was a second green revolution in Southeast Asia after the 1960s when multiple cropping became very significant for multiple countries including Viet Nam. Figure 12 shows the calculated MCI for Viet Nam and the sources used; most sources indicate a rapid growth in MCI (Lam, 2004; Chen et al., 2012; Xiao et al. 2006). FAOstat (n.d.) shows a decreasing MCI, but this is likely because they include fallow land in their calculations. Constant fertilizer use is expensive, and it is cheaper to let the land recover naturally. The land that is in use has a higher MCI, but the average is brought down if the fallow land is included. Figure 13 shows the comparison with HYDE, the numbers used by HYDE do not show a significant increase between 1985 and 2002 and the average is also lower.

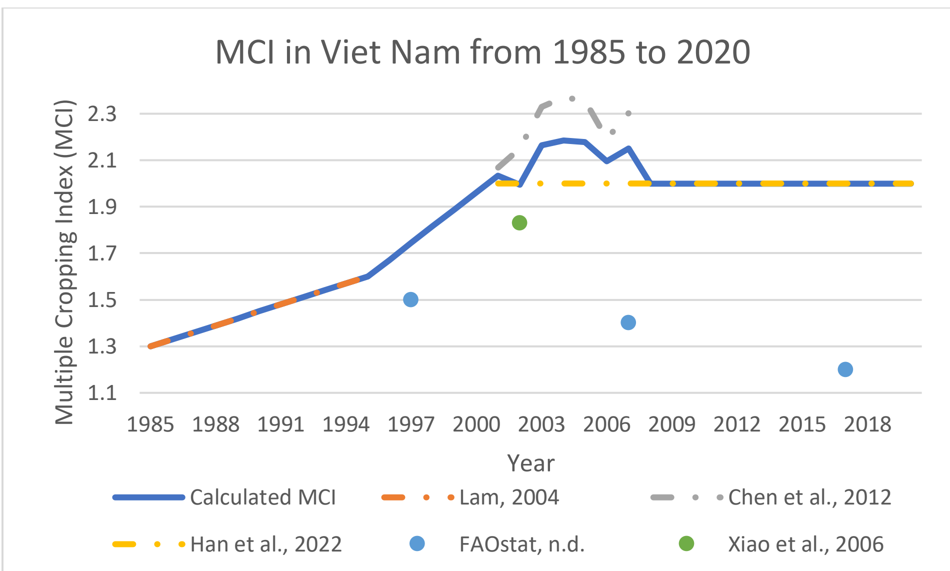

Figure 12. The MCI graph for China, shows a rapid increase in MCI from 1985 to 2001, and stagnation or decrease afterwards.

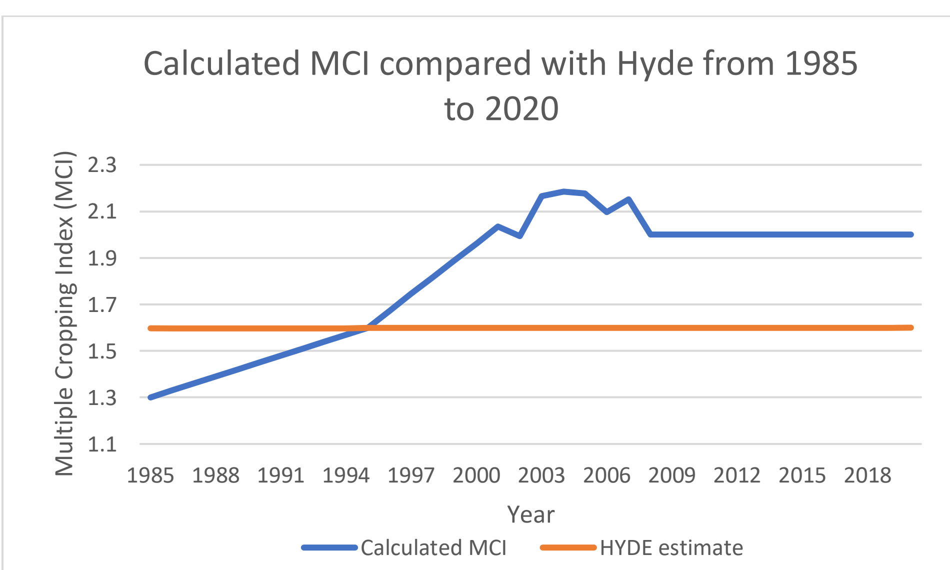

Figure 13. The calculated MCI from figure 12 compared with the MCI used in HYDE from 1985 to 2020.

Myanmar

There were few sources for multiple cropping in Myanmar, so there is a large uncertainty in the MCI between 1985 in 2014 as seen in Figure 14. The last two points by Torbick et al. (2017) show FAO data for 2013 and satellite imaging for 2014 showing a large disparity between official figures and satellite imaging. HYDE again does not show a strong increase like the calculated MCI does, it is however close to what was calculated and could be used (Figure 15).

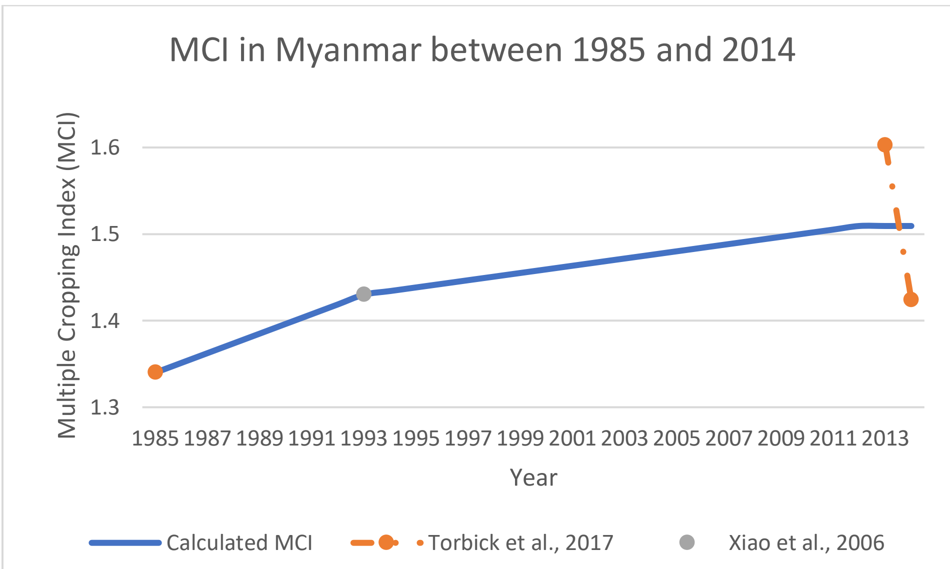

Figure 14. The MCI graph for Myanmar, showing a relatively slow increase in MCI from 1985 to 2014.

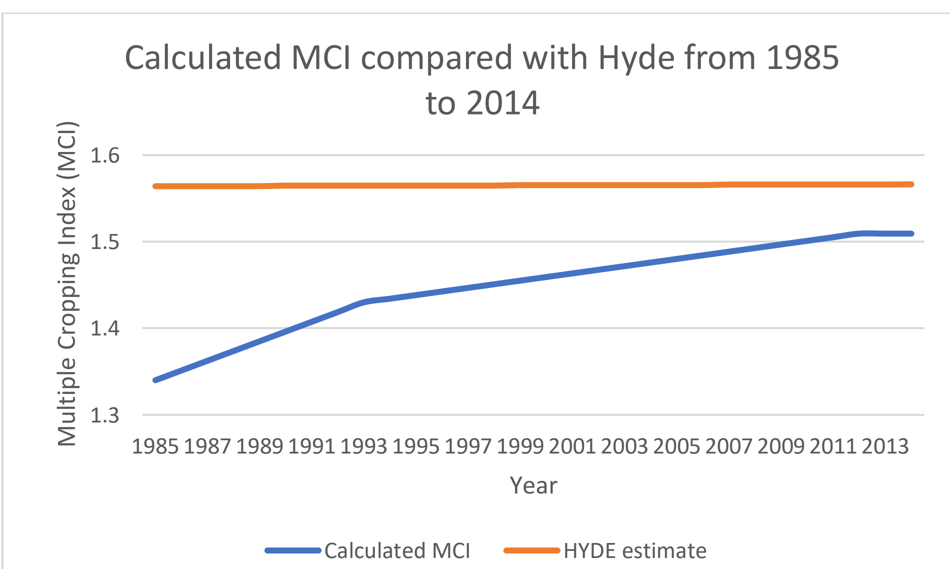

Figure 15. The calculated MCI from figure 14 compared with the MCI used in HYDE from 1985 to 2014.

Cambodia, Laos, Malaysia, and Thailand

These four countries are located next to each other and will have a cropping intensity that is like that of the others. Viet Nam which neighbours three of these countries is not included in this group because the fertile Mekong and Red River Deltas allow for a remarkably high MCI compared to the rest. Cambodia, Laos, Malaysia, and Thailand averaged an MCI of 1.25 between 1999 and 2013. HYDE used an MCI of 1.57 for these countries like China, which seems to be a little too high, though the calculated MCI varied over time (figure 16) so this could still be possible.

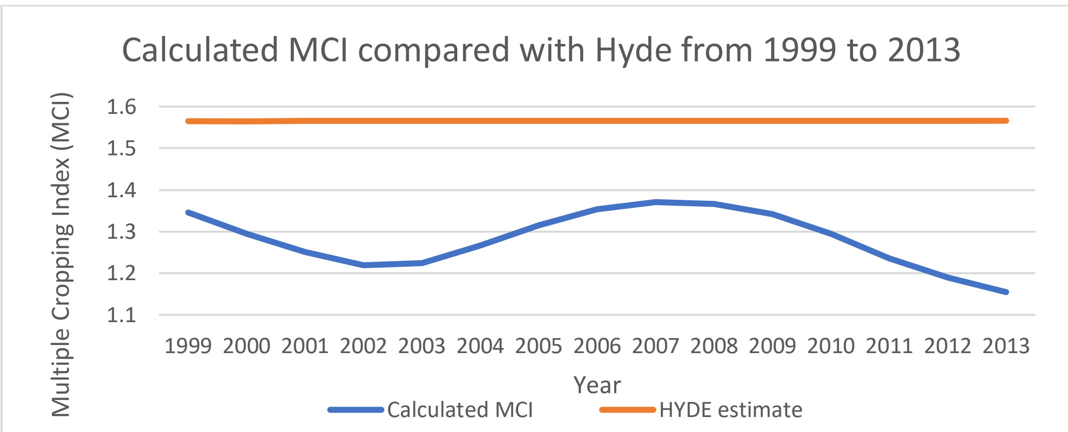

Figure 16. The MCI calculated for Cambodia, Laos, Malaysia, and Thailand compared to the estimate used by HYDE.

Japan and Korea

There was only one source for Japan and Korea that had an MCI, and it was a cropping intensity dataset for the Asian monsoon region by Han et al. (2022). They provided a 20-year average for MCI and Japan, and the Democratic People's Republic of Korea, and the Republic of Korea it gave an average of 1.03, 1.0, and 1.0, respectively. This means that there was no significant amount of multiple cropping in these countries. HYDE has an MCI of 1 for Japan, but for Korea it uses the MCI of China, which is much higher.

Nepal and Bhutan

Both countries are quite mountainous and will likely have a similar MCI to each other. There were no sources for Bhutan, but Nepal did have information from Xiao et al. (2006). Furthermore, there was a source for Tibet by G. Zhang et al. (2013), which has a similar topography. Xiao et al. (2006) found an MCI of 1.07, while G. Zhang et al. (2013) argued that the areas suitable for multiple cropping were increasing, but most farmlands were still single cropped, and few areas had rice according to the literature they found. HYDE used an MCI of 1.0 for Bhutan but used the same MCI for Nepal as that for China, which is much higher than what the literature shows.

The Philippines and Indonesia

The Philippines and Indonesia are both island countries that are relatively close to each other which could indicate that their MCI is also similar, but there are not enough sources to confirm this. According to Xiao et al. (2006), the MCI in Indonesia was 1.4 compared to 1.7 in the Philippines, and according to Langeveld et al. (2014), the MCI of Indonesia further decreased to 1.21. According to Han et al. (2022) however, the MCI in both countries was on average 1.9 between 2001 and 2020. According to HYDE the MCI in Indonesia was 1.4 like in India and the Philippines was 1.57 like in China. The data from HYDE does not seem to be significantly different but there are too few sources to confirm this.

Discussion

Interpretation

Significant differences were found by this paper compared with those used in HYDE. The date when the MCI starts increasing in HYDE is much earlier than what would be expected based on the sources found here. This means that HYDE overestimates the impact of multiple cropping for most if not all of history. It also means that the second green revolution (Rahman, 2010) is not visible in the MCI changes from the 1960s to the 2010s.

Some countries have no multiple cropping or multiple cropping is not common enough to significantly impact the land cover in those countries. This is the case for mountainous regions such as Bhutan and Nepal, and for the Korean peninsula and Japan where the monsoon season is not as strong and does not provide enough rainfall for multiple cropping. On the other hand, countries such as India, Cambodia, Laos, Myanmar, and Thailand had relatively stable MCI that did not increase significantly in the last few decades. Bangladesh, Viet Nam, and Myanmar on the other hand experienced rapid MCI growth thanks to the green revolution (Rahman, 2010). China is the outlier as it also experienced a significant decrease in MCI, caused by the movement of agricultural land from the fertile eastern coast to the low-quality soils in the west (B. Qiu et al., 2017).

Therefore, we can answer the research question: how does multiple cropping differ in countries in Asia, how can these differences be explained, and how can they be applied to land cover databases? The rice-growing countries in Asia can differ significantly from each other, the regions with a higher amount of rainfall during the monsoon season and those with extensive irrigation systems usually have more multiple cropping. Richer countries can afford the costs of year-round irrigation, seeds for multiple harvests, and mechanization to allow for quick harvesting and sowing. Land cover databases could benefit from adding these distinctions and improving how the MCI is interpolated and hindcasted.

Limitations

The study of multiple cropping is a recent development and there have been many developments to the accuracy in the last decades. Older studies relied on regional or country-level census data, but this had some limitations. China for example only tallied cropland losses which artificially inflated their yield and distorted the MCI (Yang & Li, 2000; Lin & Ho, 2003). The effect of this lessened as remote sensing developed as a field and higher-quality satellite images became available with newer satellites.

Image resolution

Higher-resolution satellite images and a higher frequency of images both correspond to higher average accuracies (L. Yu et al., 2013). Additionally, many regions in Asia have extended periods when clouds cover large regions of countries, early sources had difficulty correctly predicting the ground below while newer sources recommend radar or microwave imagery, or geostationary sensors (L. Yu et al., 2013; Gray et al., 2014; Xiang et al., 2019).

Secondary sources

Much of the literature on multiple cropping uses data from statistical agencies and government or NGO websites, but it is difficult to check this data after years or decades have passed. Some papers such as Xiao et al. (2006) reference up to a dozen sources, from which only 2 are still available. Sources that reference the FAO also run into the issue that the entire FAOSTAT website was updated between 2013 and 2015, and links that lead to the old website do not redirect to the corresponding page or document on the new website. Language also plays a key role, as many countries do not provide their statistical data in English or had it locked behind paywalls.

Limited and conflicting information

There was some difficulty in gathering enough information for each country, some had little research while others had large gaps in data. While the research was abundant for China, India, and Bangladesh, countries like Sri Lanka, Cambodia, Bhutan, and Laos had limited data. The gaps in data had to be taken from neighbouring countries or interpolated from data points of various sources. This introduces some uncertainty as the methodologies can differ between them, or the year may be exceptionally bad for multiple cropping due to natural disasters for example. Whenever possible trendlines were used as the MCI between years could differ but the average could show a trend instead.

The results of this research are still useful, however. There are major differences between the MCI used in HYDE and calculated here that cannot be explained by unreliable data or year-by-year variations. Furthermore, HYDE uses an MCI that starts rising much earlier than sources claim could be realistic. While more data and more agreement between sources would help it would not drastically change the MCI for Bangladesh, India, China, or Viet Nam, as these had enough sources to make a useful graph with. Satellite imaging will continue to improve in the future and as more papers focus on multiple cropping these issues will likely be resolved.

Implications

Multiple cropping can have a significant impact on the land cover in a country which can lead to large inconsistencies if not accounted for. This paper shows the large inconsistencies between many sources more clearly but did not focus on the reasons for these differences too heavily. Further research may explore this dimension instead.

Many sources could not be examined in this timeframe. Most of the sources that were not used included land use datasets that provided the locations in which multiple cropping occurs. The differences in MCI between literature and HYDE are now visible, but the spatial differences in where multiple cropping takes place within a country have not been explored. Future research could focus on this dimension instead.

Some have argued for increasing multiple cropping to keep pace with population growth in Asia and Africa. Countries such as Bangladesh and Viet Nam show that large increases in MCI could be accomplished in more countries, especially with the use of irrigation, but this would be extremely expensive. The benefits from the increased production would have to be weighed with the increased monetary and ecological costs before anything is implemented.

Conclusions

The questions that this researched aimed to answer were: how does multiple cropping differ in countries in Asia, how can these differences be explained, and how can they be applied to land cover databases?

There were large differences in multiple cropping. Countries in East Asia (Figure 17) had low amounts or no multiple cropping (Japan and Korea) while the MCI in China was decreasing. Countries in South Asia had an average MCI (India, Sri Lanka, Myanmar) and an outlier in Bangladesh that had a very high MCI. Countries in Southeast Asia had an MCI somewhere in between East and South (Cambodia, Laos, Malaysia, and Thailand), Viet Nam had a very high MCI, while there was not enough information to conclusively decide for the Philippines and Indonesia.

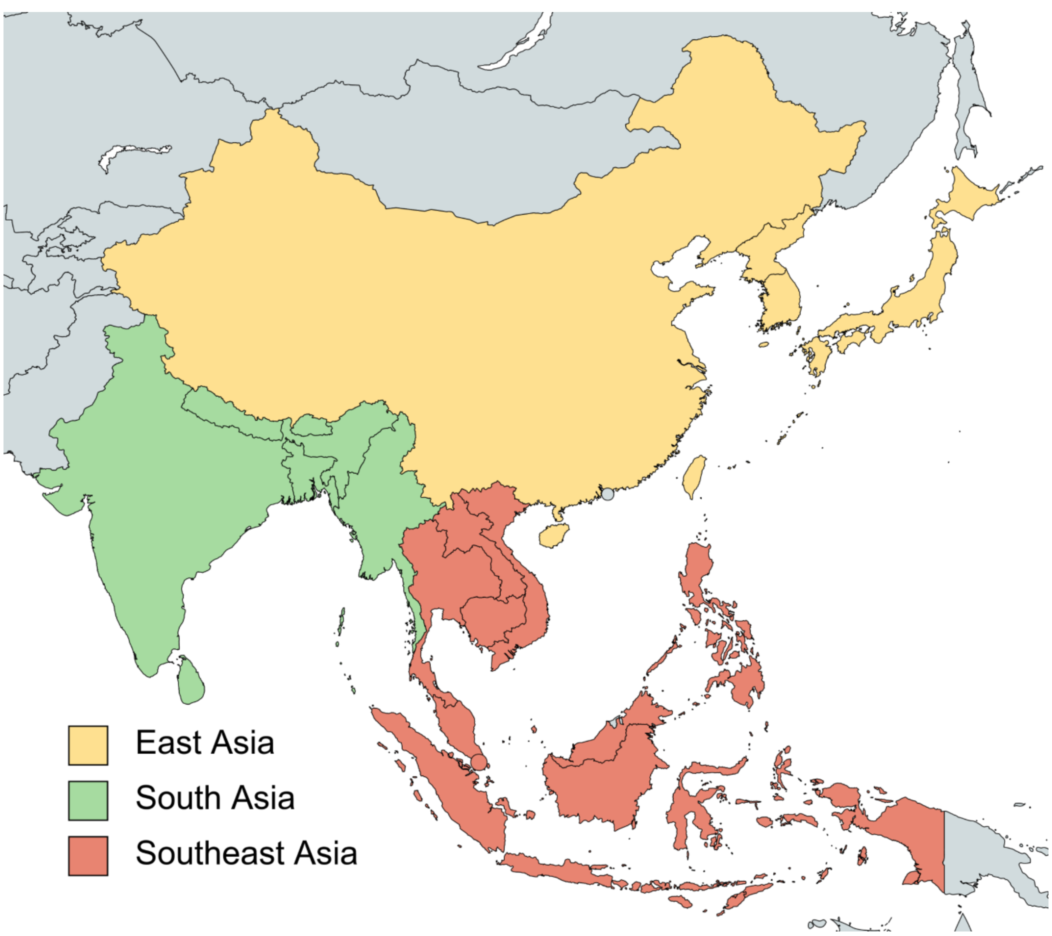

Figure 17. The countries that were examined in this research divided into three regions.

Asia is a diverse continent and there are large social, topographical, economic, and ecological differences, these factors also heavily influence multiple cropping in Asia. Countries that have a strong monsoon season and as such enjoy high amounts of rainfall do not have to finance expensive irrigation projects. Richer countries can afford to buy seeds for multiple harvests each year and to apply fertilizers multiple times a year. Countries at higher elevations have shorter growing seasons which means that multiple cropping cannot occur at all. China has to contend with population growth and the growing cities that come with it are pushing agriculture to less fertile lands. Whereas Viet Nam has the Mekong Delta and Red River Delta that allow for very heavy intensification.

While HYDE does have some differences with the numbers found in and calculated from the literature these could be fixed by changing the growth curve of MCI and changing the final value for certain countries. HYDE linearly interpolates the MCI for all countries from its starting date of 10,000 BC, which predates multiple cropping by 11,000 years at least. Furthermore, the MCI only started growing rapidly in the last century, not linearly from the date of first multiple cropping. This means that HYDE overestimates multiple cropping in the past for all countries, it underestimates a few in recent years as well due do differences with information found in the literature. Certain countries also showed decreases in MCI which were not modelled in HYDE, but it is uncertain if this occurred or if year-by-year variations impacted the measurement in sources. Uncertainty in the literature is also high, sources disagree on the amount of land under multiple cropping in dates close to each other.

Acknowledgements

I would like to thank Kees Goldewijk for providing information on the workings of HYDE, the data used in the calculations for HYDE, and for giving helpful feedback on the thesis.

References

Ackerman, F., DeCanio, S. J., Howarth, R. B., & Sheeran, K. A. (2009). Limitations of integrated assessment models of climate change. *Climatic Change*, *95*(3–4), 297–315. https://doi.org/10.1007/s10584-009-9570-x

AgLEDx Resource Platform. (2022, August 23). *Flooded rice systems: Emissions & mitigation strategies » AgLED*. https://agledx.ccafs.cgiar.org/emissions-led-options/production-systems/flooded-rice/

Ara, I., Lewis, M. A., & Ostendorf, B. (2016). Spatio-temporal analysis of the impact of climate, cropping intensity and means of irrigation: an assessment on rice yield determinants in Bangladesh. *Agriculture & Food Security*, *5*(1). https://doi.org/10.1186/s40066-016-0061-9

Biradar, C., & Xiao, X. (2011). Quantifying the area and spatial distribution of double- and triple-cropping croplands in India with multi-temporal MODIS imagery in 2005. *International Journal of Remote Sensing*, *32*(2), 367–386. https://doi.org/10.1080/01431160903464179

Brouwer, C., Prins, K., & Heibloem, M. (1989). *Irrigation Water Management: Irrigation Scheduling*. Food and Agriculture Organization.

Canisius, F., Turral, H., & Molden, D. (2007). Fourier analysis of historical NOAA time series data to estimate bimodal agriculture. *International Journal of Remote Sensing*, *28*(24), 5503–5522. https://doi.org/10.1080/01431160601086043

Chen, C., Son, N. T., & Chang, L. (2012). Monitoring of rice cropping intensity in the upper Mekong Delta, Vietnam using time-series MODIS data. *Advances in Space Research*, *49*(2), 292–301. https://doi.org/10.1016/j.asr.2011.09.011

Dalrymple, D. G. (1971). *Survey of Multiple Cropping in Less Developed Nations*.

Ellis, E. C., & Wang, S. (1997). Sustainable Traditional Agriculture in the Tai Lake Region of China. *Agriculture, Ecosystems & Environment*, *61*(2–3), 177–193. https://doi.org/10.1016/s0167-8809(96)01099-7

Estel, S., Kuemmerle, T., Levers, C., Baumann, M., & Hostert, P. (2016). Mapping cropland-use intensity across Europe using MODIS NDVI time series. *Environmental Research Letters*, *11*(2), 024015. https://doi.org/10.1088/1748-9326/11/2/024015

FAO. (2021). World Food and Agriculture - Statistical Yearbook 2021. In *FAO eBooks*. https://doi.org/10.4060/cb4477en

FAO, IFAD, UNICEF, WFP, & WHO. (2022). The State of Food Security and Nutrition in the World 2022: Repurposing food and agricultural policies to make healthy diets more affordable. In *FAO eBooks*. FAO. https://doi.org/10.4060/cc0639en

FAOstat. (n.d.). *Viet Nam*. Retrieved June 23, 2023, from http://faostat.fao.org/static/syb/syb_237.pdf

Frolking, S., Qiu, J., Boles, S., Xiao, X., Liu, J., Zhuang, Y., Li, C., & Qin, X. (2002). Combining remote sensing and ground census data to develop new maps of the distribution of rice agriculture in China. *Global Biogeochemical Cycles*, *16*(4), 38–10. https://doi.org/10.1029/2001gb001425

Frolking, S., Yeluripati, J., & Douglas, E. M. (2006). New district-level maps of rice cropping in India: A foundation for scientific input into policy assessment. *Field Crops Research*, *98*(2–3), 164–177. https://doi.org/10.1016/j.fcr.2006.01.004

Fukagawa, N. K., & Ziska, L. H. (2019). Rice: Importance for Global Nutrition. *Journal of Nutritional Science and Vitaminology*, *65*(Supplement), S2–S3. https://doi.org/10.3177/jnsv.65.s2

Goldewijk, K. K., Beusen, A. H. W., Doelman, J. C., & Stehfest, E. (2017). Anthropogenic land use estimates for the Holocene – HYDE 3.2. *Earth System Science Data*, *9*(2), 927–953. https://doi.org/10.5194/essd-9-927-2017

Gray, J. M., Friedl, M. A., Frolking, S., Ramankutty, N., Nelson, A. T., & Gumma, M. K. (2014). Mapping Asian Cropping Intensity With MODIS. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *7*(8), 3373–3379. https://doi.org/10.1109/jstars.2014.2344630

Greenland, D. J. (1997). *The Sustainability of Rice Farming*. Cabi.

Gumma, M. K., Thenkabail, P. S., Teluguntla, P., Rao, M., Mohammed, I. A., & Whitbread, A. M. (2016). Mapping rice-fallow cropland areas for short-season grain legumes intensification in South Asia using MODIS 250 m time-series data. *International Journal of Digital Earth*, *9*(10), 981–1003. https://doi.org/10.1080/17538947.2016.1168489

Han, J., Zhang, Z., Luo, Y., Cao, J., Zhang, L., Zhuang, H., Cheng, F., Zhang, J., & Tao, F. (2022). Annual paddy rice planting area and cropping intensity datasets and their dynamics in the Asian monsoon region from 2000 to 2020. *Agricultural Systems*, *200*, 103437. https://doi.org/10.1016/j.agsy.2022.103437

Ho, P. T. (1956). Early-Ripening Rice in Chinese History. *The Economic History Review*, *9*(2), 200–218. https://www.jstor.org/stable/2591742

Humbolt State University. (2019). *Learning Module 6.2 Accuracy Metrics*. Humbolt State University GSP 216 Introduction to Remote Sensing. Retrieved June 6, 2023, from https://gsp.humboldt.edu/olm_2019/courses/GSP_216_Online/lesson6-2/metrics.html

India - Global yield gap atlas. (n.d.). http://www.yieldgap.org/india

Lam, N. D. (2004). POST-HARVEST RESEARCH AND DEVELOPMENT IN VIET NAM. *Economics*. https://www.un-csam.org/sites/default/files/2021-01/post-harvest%20Research%20and%20Development%20in%20Vietnam%20.pdf

Langeveld, J., Dixon, J., Van Keulen, H., & Quist-Wessel, P. M. F. (2014). Analyzing the effect of biofuel expansion on land use in major producing countries: evidence of increased multiple cropping. *Biofuels, Bioproducts and Biorefining*, *8*(1), 49–58. https://doi.org/10.1002/bbb.1432

Li, L., Friedl, M. A., Xin, Q., Gray, J. M., Pan, Y., & Frolking, S. (2014). Mapping Crop Cycles in China Using MODIS-EVI Time Series. *Remote Sensing*, *6*(3), 2473–2493. https://doi.org/10.3390/rs6032473

Lin, G. C. S., & Ho, S. B. (2003). China’s land resources and land-use change: insights from the 1996 land survey. *Land Use Policy*, *20*(2), 87–107. https://doi.org/10.1016/s0264-8377(03)00007-3

Mainuddin, M., & Kirby, M. (2015). National food security in Bangladesh to 2050. *Food Security*, *7*(3), 633–646. https://doi.org/10.1007/s12571-015-0465-6

Mainuddin, M., Kirby, M., Chowdhury, R. a. R., & Shah-Newaz, S. M. (2014). Spatial and temporal variations of, and the impact of climate change on, the dry season crop irrigation requirements in Bangladesh. *Irrigation Science*, *33*(2), 107–120. https://doi.org/10.1007/s00271-014-0451-3

Martello, R. D. (2022). The origins of multi-cropping agriculture in Southwestern China: Archaeobotanical insights from third to first millennium B.C. Yunnan. *Asian Archaeology*, *6*(1), 65–85. https://doi.org/10.1007/s41826-022-00052-2

Perkins, D. H. (2017). *Agricultural Development in China, 1368-1968*. Routledge.

Promkhambut, A., & Rambo, A. T. (2017). Multiple Cropping after the Rice Harvest in Rainfed Rice Cropping Systems in Khon Kaen Province, Northeast Thailand. *Southeast Asian Studies*, *6*(2), 325–338. https://doi.org/10.20495/seas.6.2_325

Qiu, B., Lu, D., Tang, Z., Song, D., Zeng, Y., Wang, Z., Chen, C., Chen, N., Huang, H., & Xu, W. (2017). Mapping cropping intensity trends in China during 1982–2013. *Applied Geography*, *79*, 212–222. https://doi.org/10.1016/j.apgeog.2017.01.001

Qiu, J., Tang, H., Frolking, S., Boles, S., Li, C., Xiao, X., Liu, J., Zhuang, Y., & Qin, X. (2003). Mapping Single-, Double-, and Triple-crop Agriculture in China at 0.5° × 0.5° by Combining County-scale Census Data with a Remote Sensing-derived Land Cover Map. *Geocarto International*, *18*(2), 3–13. https://doi.org/10.1080/10106040308542268

Rahman, S. (2010). Six decades of agricultural land use change in Bangladesh: Effects on crop diversity, productivity, food availability and the environment, 1948-2006. *Singapore Journal of Tropical Geography*, *31*(2), 254–269. https://doi.org/10.1111/j.1467-9493.2010.00394.x

Ray, D. K., & Foley, J. A. (2013). Increasing global crop harvest frequency: recent trends and future directions. *Environmental Research Letters*, *8*(4), 044041. https://doi.org/10.1088/1748-9326/8/4/044041

Rita, D. M., Xiaorui, L., & Fuller, D. Q. (2021). Two-season agriculture and irrigated rice during the Dian: radiocarbon dates and archaeobotanical remains from Dayingzhuang, Yunnan, Southwest China. *Archaeological and Anthropological Sciences*, *13*(4). https://doi.org/10.1007/s12520-020-01268-y

Sakamoto, T., Van Phung, C., Kotera, A., Nguyen, K. S., & Yokozawa, M. (2009). Analysis of rapid expansion of inland aquaculture and triple rice-cropping areas in a coastal area of the Vietnamese Mekong Delta using MODIS time-series imagery. *Landscape and Urban Planning*, *92*(1), 34–46. https://doi.org/10.1016/j.landurbplan.2009.02.002

Siebert, S., Portmann, F. T., & Döll, P. (2010). Global Patterns of Cropland Use Intensity. *Remote Sensing*, *2*(7), 1625–1643. https://doi.org/10.3390/rs2071625

Soora, N. K., Aggarwal, P. K., Saxena, R., Rani, V. S., Jain, S., & Chauhan, N. (2013). An assessment of regional vulnerability of rice to climate change in India. *Climatic Change*, *118*(3–4), 683–699. https://doi.org/10.1007/s10584-013-0698-3

Sweeney, M. M., & McCouch, S. R. (2007). The Complex History of the Domestication of Rice. *Annals of Botany*, *100*(5), 951–957. https://doi.org/10.1093/aob/mcm128

Timsina, J., & Guilpart, N. (n.d.). *Description of cropping systems, climate, and soils in Bangladesh*. Global Yield Gap Atlas. Retrieved June 10, 2023, from https://www.yieldgap.org/bangladesh

Tingting, L., & Chuang, L. (2010). Study on extraction of crop information using time-series MODIS data in the Chao Phraya Basin of Thailand. *Advances in Space Research*, *45*(6), 775–784. https://doi.org/10.1016/j.asr.2009.11.013

Torbick, N., Chowdhury, D., Salas, W., & Qi, J. (2017). Monitoring Rice Agriculture across Myanmar Using Time Series Sentinel-1 Assisted by Landsat-8 and PALSAR-2. *Remote Sensing*, *9*(2), 119. https://doi.org/10.3390/rs9020119

United Nations. (2022a). *The Sustainable Development Goals Report 2022*. https://unstats.un.org/sdgs/report/2022/The-Sustainable-Development-Goals-Report-2022.pdf

United Nations. (2022b, November 15). *As the world's population hits 8 billion people, UN calls for solidarity in advancing sustainable development for all*. United Nations Sustainable Development Goals. Retrieved May 29, 2023, from https://www.un.org/sustainabledevelopment/blog/2022/11/press-release-as-the-worlds-population-hits-8-billion-people-un-calls-for-solidarity-in-advancing-sustainable-development-for-all/

United Nations Department of Economic and Social Affairs, Population Division. (2021). *Global Population Growth and Sustainable Development*.

Waha, K., Dietrich, J. P., Portmann, F. T., Siebert, S., Thornton, P. K., Bondeau, A., & Herrero, M. (2020). Multiple cropping systems of the world and the potential for increasing cropping intensity. *Global Environmental Change-human and Policy Dimensions*, *64*, 102131. https://doi.org/10.1016/j.gloenvcha.2020.102131

Wahiduddin, M., Sultan, H., Rahman, S., & Zohir, S. (1994). Agricultural Growth Through Crop Diversification in Bangladesh. *ResearchGate*. https://www.researchgate.net/publication/267955618_Agricultural_Growth_Through_Crop_Diversification_in_Bangladesh

Wu, W., Yu, Q., You, L., Chen, K. J., Tang, H., & Liu, J. (2018). Global cropping intensity gaps: Increasing food production without cropland expansion. *Land Use Policy*, *76*, 515–525. https://doi.org/10.1016/j.landusepol.2018.02.032

Xiang, M., Yu, Q., & Wu, W. (2019). From multiple cropping index to multiple cropping frequency: Observing cropland use intensity at a finer scale. *Ecological Indicators*, *101*, 892–903. https://doi.org/10.1016/j.ecolind.2019.01.081

Xiao, X., Boles, S., Frolking, S., Li, C., Babu, J. Y., Salas, W., & Moore, B. (2006). Mapping paddy rice agriculture in South and Southeast Asia using multi-temporal MODIS images. *Remote Sensing of Environment*, *100*(1), 95–113. https://doi.org/10.1016/j.rse.2005.10.004

Yan, H., Xiao, X., Huang, H., Liu, J., Chen, J., & Bai, X. (2014). Multiple cropping intensity in China derived from agro-meteorological observations and MODIS data. *Chinese Geographical Science*, *24*(2), 205–219. https://doi.org/10.1007/s11769-013-0637-2

Yang, H., & Li, X. (2000). Cultivated land and food supply in China. *Land Use Policy*, *17*(2), 73–88. https://doi.org/10.1016/s0264-8377(00)00008-9

Yao, F., Xu, Y., Lin, E., Yokozawa, M., & Zhang, J. (2007). Assessing the impacts of climate change on rice yields in the main rice areas of China. *Climatic Change*, *80*(3–4), 395–409. https://doi.org/10.1007/s10584-006-9122-6

Yu, L., Wang, J. J., Clinton, N., Xin, Q., Zhong, L., Chen, Y., & Gong, P. (2013). FROM-GC: 30 m global cropland extent derived through multisource data integration. *International Journal of Digital Earth*, *6*(6), 521–533. https://doi.org/10.1080/17538947.2013.822574

Yu, Q., Van Vliet, J., Verburg, P. H., You, L., Yang, P., & Wu, W. (2018). Harvested area gaps in China between 1981 and 2010: effects of climatic and land management factors.

Environmental Research Letters, *13*(4), 044006. https://doi.org/10.1088/1748-9326/aaafe0

Zhang, G., Dong, J., Zhou, C., Xu, X., Wang, M., Ouyang, H., & Xiao, X. (2013). Increasing cropping intensity in response to climate warming in Tibetan Plateau, China. *Field Crops Research*, *142*, 36–46. https://doi.org/10.1016/j.fcr.2012.11.021

Zhang, W., Yu, Y., Huang, Y., Li, T., & Wang, P. (2011). Modeling methane emissions from irrigated rice cultivation in China from 1960 to 2050. *Global Change Biology*, *17*(12), 3511–3523. https://doi.org/10.1111/j.1365-2486.2011.02495.x

Zuo, L., Wang, X., Liu, F., & Yi, L. (2013). Spatial Exploration of Multiple Cropping Efficiency in China Based on Time Series Remote Sensing Data and Econometric Model. *Journal of Integrative Agriculture*, *12*(5), 903–913. https://doi.org/10.1016/s2095-3119(13)60308-1

Zuo, L., Wang, X., Zhang, Z., Zhao, X., Liu, F., Yi, L., & Liu, B. (2014). Developing grain production policy in terms of multiple cropping systems in China. *Land Use Policy*, *40*, 140–146. https://doi.org/10.1016/j.landusepol.2013.09.014

Appendix A, population growth in Asia

Excluding Russia, West Asia, and Central Asia

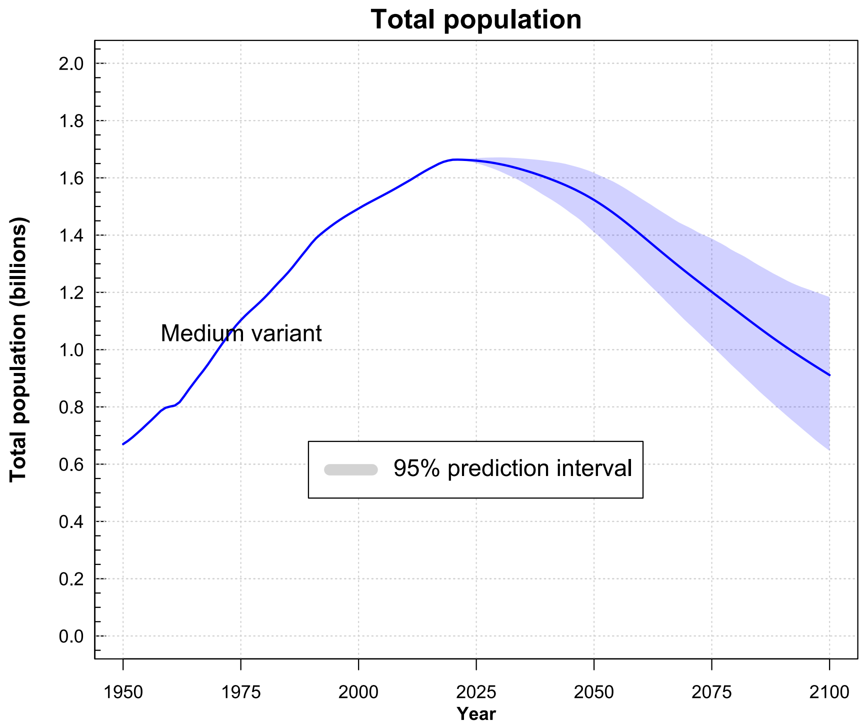

Figure I. Population decline in East Asia. The population will decrease by around 500 million from 1.65 billion to 1.15 billion (range of ±200 million) (United Nations Department of Economic and Social Affairs, Population Division, 2021).

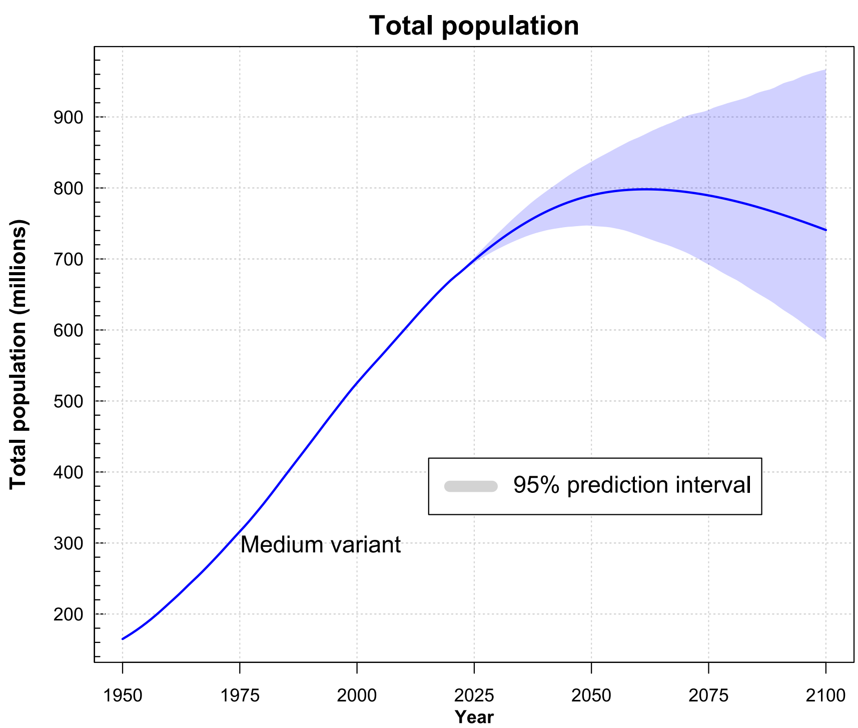

Figure II. Population increase in Southeast Asia. The population will increase by around 100 million from 700 million to 800 million people (range of ±100 million) (United Nations Department of Economic and Social Affairs, Population Division, 2021).

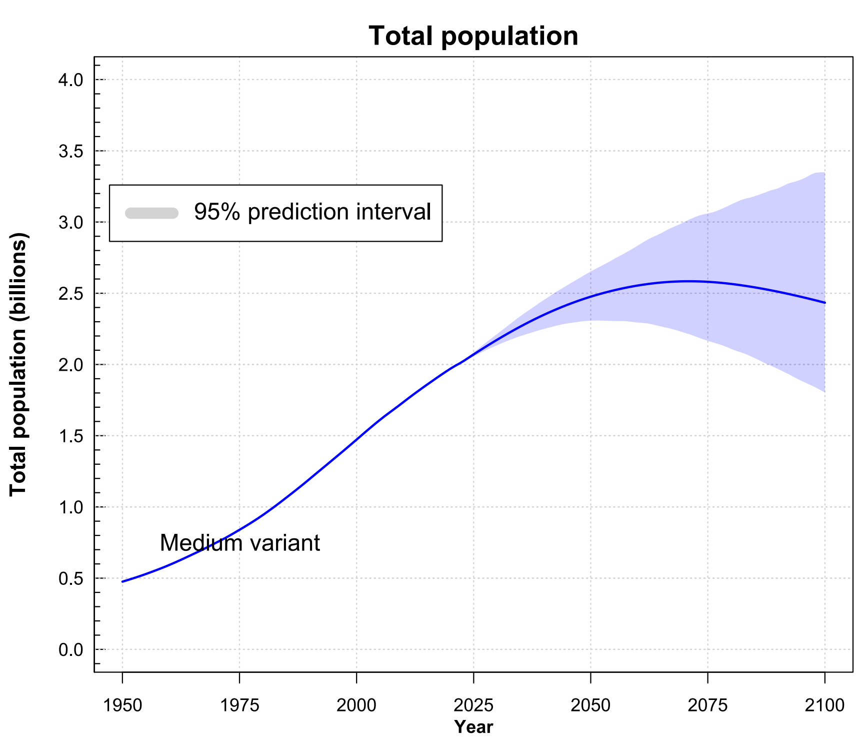

Figure III. population increase in South Asia. The population will increase by around 600 million from 2 billion to 2.6 billion people (range of ± 900 million) (United Nations Department of Economic and Social Affairs, Population Division, 2021).