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IoT-Enabled Farms and Climate-Adaptive Agriculture Technologies

Investment Lessons from Singapore

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INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE

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ABSTRACT

The adoption of climate-adaptive agricultural technologies (CAATs) for extensive (outdoor) agriculture is stalled by funding gaps experienced by governments in the Mekong countries, with negative implications on the rural farming industry, on income and job security among smallholder farmers, and on food sufficiency and access across the population. We argue that one way of helping bridge these gaps is for providers and users of CAATs for extensive agriculture to learn from the practices of those in CAATs for intensive (indoor) agriculture. Indoor CAATs are already receiving significant private-sector investment, a key reason being their ability to leverage the complementary nature of these technologies within farms that are integrated and enabled to use the so-called Internet of things (IoT). Seamlessly linking different CAATs (sensors, crop analytics, and automation) can allow for synergies that significantly boost crop yields and, in turn, the viability of investing in CAATs. We demonstrate these synergies through two case studies, one that looks at the increasing global investment in indoor CAATs and another that describes a financial viability assessment for an indoor farm in Singapore. We conclude with lessons on how these insights can be transferred to the Mekong countries, including a prototype IoT-enabled extensive farm that integrates multiple CAATs, and an investment assessment tool for translating the yield benefits into terms that investors can appreciate.

Keywords: Internet of things, IoT, investment, climate-adaptive agricultural technologies, indoor farms, Mekong, Singapore, UrbanAgInvest, private sector

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ACRONYMS

AY	average yield
CAAT	climate-adaptive agricultural technology
ERIA	Economic Research Institute for ASEAN and East Asia
FDI	foreign direct investment
IoT	Internet of things
ODA	official development assistance
PDR	People's Democratic Republic (Lao)
PFAL	plant factory with artificial lighting
PY	potential yield
RAI	RuralAgInvest
UAI	UrbanAgInvest
VRI	variable rate input

I. Problem: Underfunded Climate-Adaptive Agricultural Technologies in the Mekong Countries

a. Financing Gaps in the Mekong Countries

During the recent Workshop on Adaptation Roadmaps for Disaster Resilience and Climate Change, hosted by the Economic Research Institute for ASEAN and East Asia (ERIA), public-sector officials from Cambodia, Lao People's Democratic Republic (PDR), Myanmar, and Viet Nam, collectively referred to as the Mekong countries, discussed the common challenge of funding gaps that prevent the implementation of climate adaptation initiatives.

In Cambodia's Ministry of Agriculture, Forestry and Fisheries alone, a financing gap of more than US$187.1 million[1] was cited for climate change adaptation, based on the country's draft road map for climate change adaptation, presented at the workshop. And this is only 1 among 15 sectors deemed climate sensitive, with a total gap of $802.6 million that represents 92.7 percent of the total adaptation financing demand across all of these sectors (Cambodia Department of Climate Change 2018). The other Mekong countries did not present any budgets for climate change financing, but experts and other participants agreed that the financing gap was also relevant to other Mekong countries. Moreover, representatives from these countries shared that they regularly apply and compete for similar international grants and loans to make their agricultural sectors more resilient to environmental changes.

Changing temperatures and irregular precipitation have caused losses in crop production, through such mechanisms as less conducive growing temperatures, the emergence of pests and diseases, and droughts and floods that either clear acres of land before crops can be harvested or postpone planting schedules. For instance, in 2017 alone, Cambodia suffered damage to 8,646 hectares of maize-planted land from floods and droughts, and 5,846 hectares of paddy area were damaged by pests and disease in Myanmar (AFSIS 2017). Such losses have negative long-term implications on food sufficiency and access. A 70 percent increase in global food demand is expected by 2050 (FAO 2015), yet crop yields (mostly in

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[1] All dollar amounts are in US dollars.

extensive agriculture—that is, farming outdoors in the fields) are expected to decline in certain regions. Rice yields, in fact, are expected to fall by 8–14 percent in South Asia and in East Asia and the Pacific (Nelson et al. 2009). If supply does not catch up with demand, then food prices are expected to increase (Nelson et al. 2009), resulting in less affordable food and worse nutrition outcomes.

The relationship between climate change and food production is also relevant to job and income security. The Mekong region has been known as the rice bowl of the world, giving it a high dependency on agriculture for jobs and income. Reduced yields will thus likely impact farming populations, who are likely to feel a double pinch from both reduced incomes and higher food prices. These impacts can be worse on smallholders, who, owing to the size of their farm plots, typically have insufficient capital to buffer against disruptions. Yet more than 80 percent of the world's smallholder farmers reside in the Asia-Pacific region (Thapa 2009).

b. Potential to Learn from High Investment in Intensive CAATs in Singapore

What is ironic is that the Mekong countries, who so depend on agriculture for jobs, income, and food security, are finding it difficult to draw the needed funding for climate-adaptive agricultural technologies (CAATs), whereas Singapore, a country that imports most of its food and in which agriculture contributes a very small share of gross domestic product and jobs, has an abundance of investment in these technologies, albeit in indoor agriculture.

Singapore lies very much on the other end of the spectrum from the Mekong countries, with sufficient per capita income to import the food it needs, even during times of disruption. Technically, the country doesn't even need agriculture for survival purposes. Rather, it sees agriculture as an option to reduce price fluctuations for domestically consumed food. Of late, it has started to see in agriculture the potential to create jobs and value-added for the country's economic growth. In fact, its farmers are by themselves investing in CAATs as a way to uncover the commercial potential of the sector. All of this is in spite of higher prices for land and other inputs.

There may be many reasons why Singapore and the Mekong countries have followed divergent paths in CAAT investment, and in particular for why CAATs are a seized investment opportunity in the former and an underfunded fiscal item in the latter. Some of these reasons may be fundamental—that is, structural. CAATs are a high-cost endeavor that requires significant up-front investment. Singapore's high per-capita income and investment-friendly ecosystem allow individuals and companies possessing capital to make these initial investments, whereas both incomes and the investment environment are less developed in Mekong countries.

However, this insight is not so helpful to Mekong countries, because economic development is already being pursued as a state strategy, and these countries cannot wait for their per capita income levels and investment climate to match Singapore's before bridging CAAT financing gaps. Food insecurity could worsen, given the rate at which conditions for growing crops are worsening or becoming more uncertain.

II. Diagnosing the CAAT "Market": Challenges in Scaling

The private sector would not need government prodding to invest in CAATs if the returns from such investments were higher than returns on other alternatives. We therefore shift our analysis to inefficiencies in markets for CAATs, which could be a factor preventing private investment in this sector.

a. Demand, Supply, and Coordination Challenges

We frame the CAAT market as follows. In this market, *products* refer to the CAATs themselves, rather than the food that farmers produce. Correspondingly, the *providers* of CAATs are the technological firms, rather than the farmers. And finally, the ones who *demand* the CAATs are the farmers, governments, and private investors who take part in the actual agricultural production processes. CAATs can be broadly categorized as detailed in Box 1.

Box 1: General classification of CAATs

1. **Decision analytics software**, which informs farmers on the appropriate crops to grow for each agroclimatic area or region, the right timing of planting and harvesting, and the quantities of water and nutrients to employ
2. **Environmental sensors**, such as satellites, drones, and flood gauges
3. **Software for processing sensor data** and converting it into useful information that feeds into decision-making analytics
4. **Variable-rate input technologies**, which automate the process of calibrating the quantity of water and nutrients fed to plants or, under controlled growing conditions (greenhouses, indoor farms), adjust these conditions

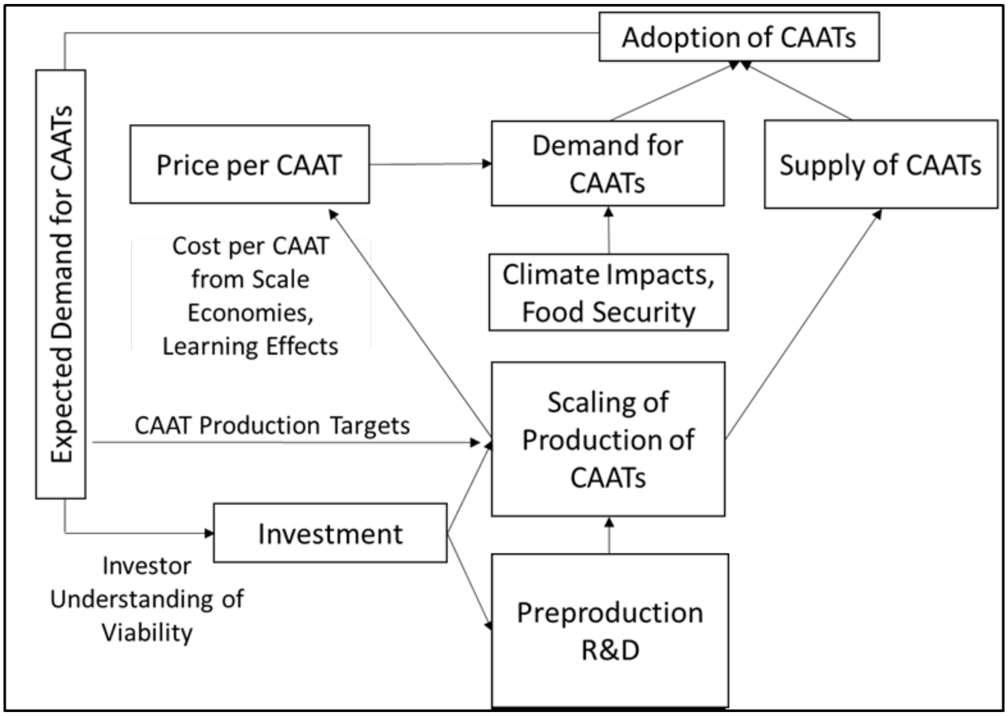
5. **Biotechnology**, which feeds into the pool of seeds that can be tapped for better resilience to climate-induced environmental stressors (droughts, floods, pests, and diseases)
6. **Technologies for logistics and storage infrastructure**, to minimize waste in the process of transporting and storing food

Source: Authors.

Note: Benefits from these technologies would be more pronounced in the face of climate change, but even without climate change, they can still improve present practices.

Within this framing of the CAAT "market," Figure 1 provides our hypothesis on factors that may allow CAATs to be brought to scale.

Figure 1: Framework for scaling CAATs



Source: Authors.
Note: CAAT = climate-adaptive agricultural technology; R&D = research and development.

One challenge shown in Figure 1 relates to demand. Even if CAATs do have positive climate adaptation and food security impacts, insufficient interest or capacity (funding) may still keep farmers, companies, and governments from purchasing them. Under this challenge, indicated by the arrow from "price per CAAT" to "demand for CAATs," users face the problem that CAATs are too expensive.

Another challenge is from the supply side. Scale economies and learning effects that improve the efficiency of production can potentially reduce the cost for producing each unit of a CAAT, as shown by the arrow from "scaling of production of CAATs" to "price per CAAT." However, CAAT providers face a potential gap if they cannot achieve the expected economies of scale and thus cannot reduce the cost of providing CAATs.

Demand and supply challenges trail and in fact hinder one another, as in the classic chicken-egg problem. The cost of producing a CAAT can be lowered if technology providers leverage economies of scale and invest more in CAAT production, but providers will not do so if there is no certainty of demand for these CAATs. This situation is reflected by the arrow from "expected demand for CAATs" to "investment." This uncertainty and the problem of coordination thus prevent the scaling of CAATs.

b. Complementarity Requirements for Making CAATs Viable Investments

Given this framing, scaling the use of CAATs can be seen as a business problem. Each CAAT will likely have its own issues, unique to the nature of the product provided and the market catered to. Regulations, for instance, may prevent the entry of needed technologies, just as they have stalled the entry of biotech products that could have made plants more resistant to stress. Without going into these specifics, however, we discuss potential issues that apply to CAATs in general.

A key problem common to all CAATs is large variation in the benefits that adopters can receive if they purchase one type of CAAT at a time:

- For instance, buyers of decision analytics software (technology 1) may not be able to make full use of the product without the appropriate inputs, which depend on both environmental sensors (technology 2) and software for processing the sensor data (technology 3).
- Furthermore, information drawn from the first three technologies may be challenging or expensive to implement manually through paid labor, so variable-rate input technologies, or VRIs (technology 4), are needed to maximize their use.

- Similarly, long-term improvements in seeds to make them more climate resilient can be achieved through biotechnology (technology 5), but the impact of this technology can be maximized if coupled with the previous four technologies.
- Finally, the benefits from improving logistics and storage infrastructure (technology 6) will be maximized only if a large quantity of food passes through the infrastructure, which in turn depends on the first five technologies. Conversely, failure to improve logistics and storage infrastructure could prevent food products from reaching the markets, which could, in turn, disincentivize food companies from investing in technologies that increase yields.

The examples above demonstrate that CAATs are interdependent because there will always be factors beyond a technology's scope. Without the needed complementarity, the projected benefits of any technology are reduced through higher uncertainty about the returns that it can earn.

Achieve the necessary complementarity through combinations of technologies, and adoption of CAATs can be scaled rapidly; fail to achieve it, and regardless of how much of the technology is imported, CAAT adoption is less likely to be scaled. Between these two alternatives, the latter is more likely, given the low rate of CAAT scaling observable today. The failure to achieve this complementarity of technologies thus serves as a bottleneck to scaling CAATs.

c. Success of Complementary Technologies in Indoor Farms

Today, an extensive smallholder farm (that is, one that grows food outdoors, in the fields) that utilizes the full suite of technologies highlighted here still does not exist in the Mekong region. This is perhaps the reason that CAATs for extensive farms have not yet been scaled. Further, the lack of such farms makes the concept of a CAAT-empowered extensive farm difficult to prove, leaving it a theoretical concept with limited implications for improving agricultural extension practices.

In light of these constraints on research, we turn to an area in which CAATs have been successfully utilized, indoor farms. Indoor farms are different from extensive farms primarily in terms of the intensity of use of space. Whereas farming in the fields grows plants in a single, horizontal layer, farming indoors commonly involves growing plants in multiple layers.

The indoor plant-growing environment is also different from the extensive farm in the inputs it uses for growing vegetables. Because very limited sunlight (and in some cases, no sunlight) can reach indoors, LED lighting is used to provide the plants with the needed wavelengths of light radiation for growth. The closed indoor growing environment likewise requires technologies for maintaining ideal temperatures and levels of humidity. To compensate for the absence of precipitation, an indoor farming system also needs to provide water to the plants. In many cases, rather than using soil to provide nutrients, indoor systems use hydroponics, whereby nutrients are fed to the plants through the irrigation, making for soil-free production. Additional features of indoor farms are the ability to change the air composition to favor plant growth and the ability to filter incoming air to prevent insect infestations.

So we can see that compared with environment-dependent extensive agriculture, indoor agriculture can be completely independent of the natural environment and may even seem to involve an artificial environment. On the other hand, the use of a closed environment and soil-free farming significantly reduces the potential for pathogens to enter and incubate, making hydroponics-grown vegetables a safer alternative to those grown naturally outdoors.

In spite of these differences, the two types of agriculture share commonalities in terms of the combination of CAATs that can be applied (Montesclaros and Teng 2018a):

- Indoor farms also rely on decision analytics software (technology 1) to identify appropriate growing conditions to simulate (that is, temperature, humidity, wind, water, nutrients, lighting).
- Environmental sensors (technology 2) are likewise applied indoors, although instead of drones or satellites, they can be simpler devices for monitoring smaller areas, such as room thermometers, anemometers for wind speed, and pH meters to assess the pH level in the water.
- Sensor data analytic software (technology 3) is less relevant because crops can be manually inspected, although the potential remains for using drones to automate inspections.

- VRI technologies (technology 4) are more relevant in indoor farms than outdoors because the former often use circulating hydroponic systems, which present the need to coordinate water flow and nutrient release. Additionally, LED lighting substitutes for sunlight, and it too can be regulated by VRIs.
- Biotechnology (technology 5) is also relevant to indoor farms, and innovations in seeds for growing plants indoors are still in early-stage development, given that high-tech indoor farms have only recently started to gain traction. Instead of drought or submergence resistance, the seed traits targeted focus more on taste and nutrition content so as to capture a larger share of urban consumer markets.
- Last, logistics and storage infrastructure (technology 6) are even more relevant in indoor farming than outdoors, because hydroponically grown crops are more vulnerable to temperature changes, given their high water content.

The combination of technologies within high-tech indoor farms has allowed for levels of efficiency in resource use that far exceed those of traditional indoor farms. In fact, indoor farms are known as *farm factories* due to the extent to which indoor farming mimics the efficiency of factory production in manufacturing industries. Moreover, indoor farming yields, under the common practice of growing five or more layers of vegetables, can be more than five times those of extensive agriculture. Yields can be further increased, helping farmers achieve the full yield potential of plants, through use of the appropriate temperatures, humidity, water, nutrients, and combination of LED light wavelengths (that is, the proper mix of blue light, red light, and so on) at different stages of the plant's lifecycle.

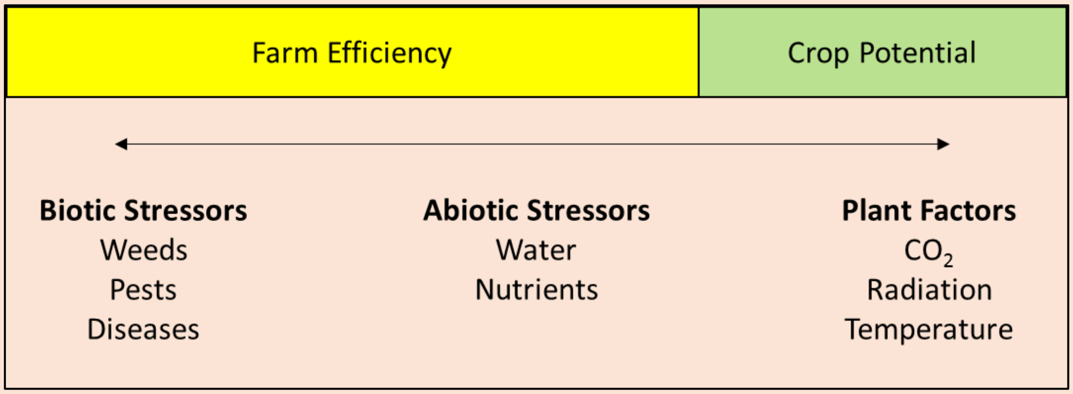
d. Potential Benefits of Complementary CAATs in Extensive Farming: Bridging Yield Gaps

An important concept in concretizing the benefits of adapting CAATs used in indoor farms to outdoor farms is the yield gap, the difference between the actual average yield, or AY (the observed yield of the median, or 50th percentile, farmer) and the potential yield, or PY (the observed yield of the best-performing, or 90th percentile and up, farmers) within a region with a rather homogenous natural resource base, weather climate, and mix of cropping systems (Box 2). Between farmers with AY and those with PY, the factors that may differ are the varieties used; the agronomic practices and inputs used; and the absence or presence of biotic and abiotic stressors, which can be a function of stress management practices.

Box 2: Spectrum of yield gaps and Internet of things applications

The scientific basis for making yield improvements—that is, bridging yield gaps—has been discussed previously by van Ittersum and colleagues (2013). However, that basis now requires reframing because the technologies of the so-called Internet of things (IoT) allow for more factors to be controlled, some of which were previously taken as givens. In this regard, Figure 2 plots the factors influencing production yields on a spectrum, from those immediately addressable with IoT technologies to those that can build on IoT technologies but require further biotechnological investments. Biotic stressors, such as weeds, pests, and diseases, and abiotic factors, such as water and nutrient shortages, can be immediately addressed with the use of IoT technologies: sensors for immediately identifying impacted sites, crop analytics for identifying the appropriate action to implement, and automation or drones for swift implementation of the recommended actions. Once gaps are bridged, further improvements can be found in biotechnology for boosting the growth potential of plants. Biotechnology, in turn, can build on crop analytics in order to ensure that new cultivars are appropriate for the sites of application.

Figure 2: Spectrum of yield gaps



Source: Authors.

The use of CAATs can have two impacts on farming yields. First, they can help bridge yield gaps by "copying" the practices of the most productive farms and, after some tailoring, "pasting" them onto the rest of the farms, using tools such as automated implementation of site-specific or calibrated computer recommendations on variety, agronomy, pest and disease detection, and biotic and abiotic stress management. In other words, better practices are implemented through integrated CAATs, enabling farms to use the technologies of the so-called Internet of things (IoT).

In Bangladesh, for instance, PYs for rice across 9 weather stations were reported to be between 2.28 and 3.21 times the AY (GYGA 2018). Similarly, in Indonesia, as shown in Table 1, PYs of rainfed rice were between 1.5 and 2.5 times the AYs across 24 weather stations (GYGA 2018).

Table 1: Average and potential yields for rainfed rice across 24 Indonesian weather stations

Station Name	Longitude	Latitude	Average Yield	Potential Yield	Potential/Actual*
Andi Jemma	120.32	-2.55	3.83	9.58	2.50
Bandung	107.60	-6.88	5.10	12.22	2.40
Banjar Baru	114.84	-3.46	4.03	8.02	1.99
Banjarnegara	109.71	-7.32	5.33	9.41	1.77
Blora	111.16	-7.20	5.17	11.02	2.13
Bone	120.20	-4.95	4.32	10.66	2.47
Citeko	106.85	-6.70	5.14	9.83	1.91
Darmaga	106.75	-6.50	5.42	9.10	1.68
Gowa	119.75	-5.63	4.91	9.05	1.84
Jakenan	111.20	-6.78	4.81	8.92	1.86
Kota Bumi	104.87	-4.84	4.58	8.17	1.78
Lombok	116.25	-8.75	4.37	9.14	2.09
Maros	119.55	-5.09	4.32	8.46	1.96
Palembang	104.70	-2.89	4.41	8.18	1.85
Parapat	98.92	2.69	5.47	11.23	2.05
Penggung	108.20	-6.50	5.37	8.67	1.61
Perak I	112.17	-7.00	5.45	8.17	1.50
Semarang	110.51	-7.25	4.03	8.88	2.20
Serang	106.34	-6.13	4.63	8.32	1.79
Sicincin	99.93	0.05	4.22	8.54	2.03
Sumbawa Besar	118.69	-8.54	5.12	9.91	1.94
Tulang Bawang	105.51	-4.51	4.30	10.75	2.50
Tuntungan	98.56	3.50	4.85	8.31	1.71
Yogyakarta	110.88	-7.97	6.07	9.45	1.56

Source: GYGA (2018).

* "Potential/actual" is the extent of increase in production capacity that can be achieved for the average farmer if he or she were able to acquire and implement the best practices of the top-performing farmers (those in the 90th percentile by yield).

The gap between PYs and AYs is thus what can be initially bridged, under two assumptions. The first assumption is that, similar to the ability of indoor farms to optimize growing conditions, computer-augmented analytics will also be able to accurately identify the driving factors for increasing yields. The second is that automation will allow for implementing these factors, given the same environmental conditions.

The other impact of CAATs is that they can expand the frontier of production possibilities, helping to boost even the highest PYs in a particular region. In Bangladesh, for instance, the rice PY measured across different regions (based on weather station data) varied from 8.00 (Rangpur, at longitude 89.27, latitude 25.73) to 9.47 (Sylhet, at longitude 91.88, latitude 24.9) tons per hectare per year. The PY between these two regions can potentially be bridged through experimenting with different cropping systems and biotechnology that can compensate for differences in precipitation and the natural resource base between these two areas.

Furthermore, there is potential to bridge yield gaps across countries. Globally, Kolda, Senegal (longitude -14.95, latitude 12.91), has the lowest rice yields, at less than a ton per hectare per year (0.73 tons), whereas Kasama, Zambia (longitude 31.14, latitude -10.22), has the highest, at 13.8 tons. To the extent that these differences reflect differences in precipitation, there is scope for computer-automated irrigation and nutrient release to bridge differences in yields. Box 2 provides further insight on the factors that may allow this to happen.

With the problem framed in this way, yields are no longer limited by the natural resource base and weather conditions, but rather by the viability of applying a diverse set of complementary CAATs. The business proposition is then quite straightforward. First, at the local level, the benefit offered by CAATs is the capability to double or even more than triple the annual yield for every unit of land farmed per year, as shown for Bangladesh (GYGA 2018). Second, there is scope to increase the PYs across areas so that they approximate the best yields in a country. Finally, the global differences in PYs can be bridged.

In the next sections, we will turn to the global growth of indoor farms and take a deep dive into Singapore's indoor farms, from which we can imagine the possibilities for bridging the Mekong countries' funding gaps in CAATs.

III. Case Study 1: The Global Hydroponics Industry

a. Development of Indoor CAAT Rationale

The global hydroponics industry provides a case for the viability of integrated CAATs. A seminal source that argues for the benefits of this type of farm is Dickson Despommier's essay "The Vertical Farm: Reducing the Impact of Agriculture on Ecosystem Functions and Services" (2005) and the book that expanded on it, *The Vertical Farm: Feeding the World in the 21st Century* (Despommier 2010).

To still be able to produce the same amount of crops with less space, Despommier proposed growing crops hydroponically on multiple layers per story, within multistory buildings, arguing that such *vertical farming* could compensate for the reduced availability of croplands, water, and other resources resulting from the environmental changes being observed globally. From a sustainability perspective, vertical farming would also allow natural landscapes to recover from practices involving high cropping intensity.

Despommier's ideas led to further thinking about indoor farming in general. Inquiry into the feasibility of indoor farms has led to further insight that they could actually be a better option than outdoor farms because their growing environments can be altered to suit the plants and because resources (including water and nutrients) can be used more efficiently in soil-free, hydroponic farming. Further exploration of these ideas has led to experiments in different types of hydroponics, as well as *aquaponics*, the integration of aquaculture with hydroponic vegetable growing.

b. Status of Indoor CAATs Globally

Indoor CAATs, in the form of plant factories with artificial lighting (PFALs), have drawn significant attention and investment over the past decade. Hydroponics markets were estimated to have a worldwide value of $226.45 million in 2016, set to grow to $724.87 million by 2023, according to a study by Stratistics

Market Research Consulting (2017). Another study, which looked comprehensively at hydroponic systems and had different country foci (for example, it names the Netherlands whereas the previous study did not), estimated their value in 2016 at $21.2 billion, expected to grow by a compound annual growth rate of 6.5 percent from 2018 to 2023, with the Netherlands currently being the largest producer of hydroponic crops (Mordor Intelligence 2018).

Kozai, Niu, and Takagaki (2016) documented the following country examples of PFALs:

- Japan has seen a rapid increase in PFALs, from just 34 in 2009 to 125 by March 2013, although the first PFAL was established as early as 1983. PFALs using LED lighting (rather than the previous fluorescent lighting) started only in 2005.
- In Taiwan, 56 new PFALs were established from 2013 to 2016. Wireless sensors are used for measuring air temperature, humidity, and light intensity to ensure uniformity across these factors for every layer planted. The nutrient level in the water is also measured using ion sensors. Plant growth and weight are also continuously monitored using cameras and weighing devices.
- In the Republic of Korea, several government-sponsored projects support PFALs, which have been accepted as a successful application of smart farming systems that converge information and communications technology. It was only in 2009, when LEDs were introduced to replace fluorescent lamps, that PFALs started up in the country, and about 30 companies were operating PFALs as of 2016.
- China had 35 PFALs as of 2013, distributed over 9 cities or provinces, with the largest being in Beijing, on 3,069 square meters of land.
- The United States had few recorded PFALs as of 2014, according to the said publication (Kozai, Niu and Takagaki 2016). Still, a number of companies were operating with high visibility, such as Gotham Greens, the first rooftop greenhouse, established in 2011 on 15,000 square feet and currently producing 100,000 pounds of fresh leafy vegetables per year (Gotham Greens 2018). Another is Freight Farms, which develops and distributes container farms measuring 40 x 8 x 9

feet, each capable of producing 2–4 tons of produce a year using less than 5 gallons of water per day (Freight Farms 2018).

- In Europe, there were approximately 160,000 hectares of land used for greenhouse purposes. The Netherlands is presently the most advanced, potentially helped by the presence of a local developer of LED lighting, Philips Horticulture LED Solutions, over the past seven years. In Basel, Switzerland, a greenhouse is being established atop an industrial roof, and in Sweden, a 17-story building has been designed as a PFAL. There are likewise two rooftop greenhouse farms in Barcelona, Spain, and two aquaponic farms in Slovenia.

IV. Case Study 2: Mainstreaming CAATs in Southeast Asia—the Case of Singapore

a. Singapore's Indoor Farming Scene

Singapore provides an example of CAAT development that Southeast Asian countries can emulate. Its small land area of 721 square kilometers is less than a thousandth of the land area of any of the Mekong countries with limited natural resources.

The Southeast Asian island city-state of Singapore depends on imports for 90 percent of its total food consumption. Its top three sources of vegetables are Malaysia, China, and Australia (AVA 2018). The past decade has seen its self-sufficiency in leafy vegetables increase from 7 percent in 2010 (Lim 2015) to 12 percent in 2017 (Chua 2017). This is partly attributable to the increase in vertical farms, from 1 in 2012 to 7 in 2016 to 26 in April 2017, as well as government co-investment in technologies relevant to these farms since 2014 (Singh 2016).

Today, several companies implement CAATs indoors. In 2014, renowned TV company Panasonic released news of Panasonic Factory Solutions Asia Pacific, the first licensed indoor vegetable farm in Singapore with controlled and optimized conditions. It was established to contribute to the country's food self-sufficiency targets in vegetables by transferring indoor farming knowledge from Japan and specializing in Japanese crops like *mizuna* (Japanese mustard greens), *ooba* (mint herb), and even *mitsuba* (wild parsley) (Panasonic 2014). The range of vegetables grown on this 1,154-square-meter farm has expanded from 8 crops in 2014 to 40 crops by 2017, and the quantity of vegetable production likewise has increased from 3.6 to 81 tons per year over the same period (Khoo 2017). Panasonic plans to double its production capacity through expanding by another 556 square meters, for an envisioned 180-ton production capacity when coupled with its vertical farming infrastructure; smart LED lighting; automated irrigation; controlled temperature, humidity, and carbon dioxide; and combination of soil-based and hydroponic growing (Khoo 2017).

Another indoor farm that has made use of controlled environments is Sustenir Agriculture, which seeks out nonnative high-value products, such as strawberries, to provide year-round (Kriwangko 2018). The company uses technologies for controlling the growing environment in what it dubs *controlled environment agriculture*, in combination with hydroponics, on a 930-square-meter indoor farm. It boasts monthly production of 3.2 tons of lettuce or 1 ton of kale on 54 square meters, which amounts to a 14- to 127-fold gain in yields over traditional outdoor agriculture, if one considers the combined effects of multiple-layer farming and yield improvements in controlled environments over uncontrolled environments (Kriwangko 2018). In addition, the farm is leveraging automation through robotic arms that can do the seeding and artificial intelligence that can monitor plant growth.

These two companies illustrate a significant degree of independence on the side of the farms; although government provides productivity incentives, these companies are not primarily dependent on the government for subsidies or support funding. Rather, the government's role has been to develop policies that allow these farms to operate, such as certification and standards development for the sector (that is, licenses to run indoor farms and to sell produce domestically), as well as to tender land for agricultural production purposes.

b. Factors Shaping the Viability of Indoor Farms

Singapore farms, as private, limited entities rather than publicly listed companies, are not required to publicly report their viability data. Among the vertical farms in Singapore, for instance, Panasonic Factory Solutions Asia Pacific has a parent company, Panasonic Corporation, but the annual report of the latter does not have disaggregated data allowing for assessment of the former. Moreover, although researchers have attempted to obtain farm data through interviews, farmers were not generally open to sharing in this manner (Montesclaros, Liu, and Teng 2018, 22). In spite of these obstacles, Montesclaros, Liu, and Teng (2018) recently published the first viability assessment of importing high-tech indoor vegetable farming technology into Singapore.

The tool used for assessing the supply-side commercial viability of indoor farms, known as UrbanAgInvest (UAI), developed by Montesclaros and Teng (2018b),[2] allows for predicting the year in which investors will break even if they invest in a combination of CAATs indoors, assumed to include VRI for temperature, water, and nutrients; LED lighting; and infrastructure for growing crops in multiple layers.

The indoor farming technology tested for adoption in Singapore was that of Spread Co., one of Japan's largest vegetable producers, based in Kyoto, with 90 percent of its retail sales in Tokyo supermarkets. The farm building spanned roughly 3,000 square meters (0.3 hectares) and was 2 to 3 stories high, with more than 14 layers of vegetable plantings using multi-tiered deep-flow hydroponics. Information was drawn from a case study of the company documented in the book *Plant Factory* (Kozai, Niu, and Takagaki 2016).

The target area for implementing this technology was 12 plots of land tendered by the government of Singapore for the purpose of high-productivity leafy vegetable production, each plot being roughly 2 hectares (AVA 2017). Thus potentially 80 of these farms could physically fit into the land area, each producing close to 700 tons of vegetables annually.

The scenario tested was whether these indoor farms would be able to capture the leafy vegetable markets that are presently based on imports. For data on the imports, we used the price and quantity of different classifications of leafy vegetables from each country source, based on trade codes and available statistics.

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[2] The tool has been copyrighted as an invention by Jose Ma. Luis Montesclaros (first inventor) and Paul Teng (second inventor/co-inventor), Reference Number 2018-259, © Nanyang Technological University, Singapore, and can be utilized via standard licensing agreements with the university, in collaboration with the inventors.

Multiple scenarios were then tested in terms of land prices; financial leveraging, with different investment sources such as public equity financing, government loans (based on long-term government bond yields), and social venture capital. Marketing channels for the food produced (such as wholesale and retail) were also tested to consider the price premiums for the vegetables produced. For instance, recent prices of vegetables sold in supermarkets could be up to 8 times the import price if the vegetables came from Australia, and up to 17 times the import price if they came from Malaysia (Giant Supermarket 2018).

The results showed that in the best case, up to 4 of the plots of land could be used viably, producing up to roughly 30,000 tons of leafy vegetables on 80,000 square meters of land, and meeting up to one-third of local consumption needs in Singapore. This assessment thus shows that investments in combinations of CAATs can be viable and provides an understanding of why investments in indoor farm CAATs in Singapore have been increasing.

V. Implications and Way Forward

a. Observations and Insights for Mekong Countries

Indoor CAATs have drawn significant investment in recent years, whereas extensive (outdoor) CAATs have seemed more a burden than an opportunity for governments. Table 2 presents some of the differences between successful and unsuccessful CAAT scaling. The following discussion looks at why indoor CAATs have scaled up, unlike extensive CAATs, to draw lessons for increasing the adoption of the latter in the Mekong countries of Cambodia, Laos, Myanmar, and Viet Nam.

Table 2: Comparison of successful and unsuccessful CAAT scaling

Variable	Successful CAAT Scaling	Unsuccessful CAAT Scaling
Type of CAAT	Indoor CAATs	Extensive (Outdoor) CAATs
Type of Market	Urbanized	Less Urbanized
Income Level	High Income	Low Income
Funding	Private Funding Entering	Gap in Funding

Source: Authors.
Note: CAAT = climate-adaptive agricultural technology.

One reason indoor CAATs are easier to scale than extensive CAATs may be that indoor agriculture cannot exist without fully integrated CAATs because the probability of a successful indoor farm depends on the extent to which ideal environmental conditions are replicated indoors. In contrast, extensive farming had existed for centuries before sensors and temperature control were possible, so it exhibits a tendency to rely more on traditional practices and local know-how.

Second, the countries where indoor CAATs have been successful are high-income countries, which are also typically more urbanized. Moreover, urban dwellers are commonly richer than rural dwellers. This wealth disparity happens through (1) urbanization economies, whereby the proximity of suppliers to consumers allows for greater potential to capture markets with products that can be tweaked to meet changing consumer tastes, and the same proximity also results in lower prices due to lower transport costs, as well as (2) agglomeration economies, whereby the proximity of suppliers to one another leads to products upstream that better respond to the needs of firms, allowing a potential to capture supplier markets. The concentration of high-income individuals within urban areas provides investors with an idea of the total market that can be captured. This in turn makes it possible to conduct preliminary commercial assessments of investing in PFALs.

Third, different levels of urbanization also give rise to different marketing strategies. Proximity gives sellers more direct access to consumers and eliminates the need for middlemen. It likewise reduces the cost of transporting the commodity, which in turn means that a lower price can be charged for the vegetables sold. In order to transfer these insights to extensive agriculture, which is commonly carried out in rural areas, it is critical to ensure the efficiency of marketing channels (including road and transport infrastructure) from "farm to fork" so that producers have sufficient access to urban and overseas markets.

A fourth reason is that there have been studies of successful integration of CAATs in indoor agriculture, whereas no such study of integration has yet been made for extensive agriculture in the Mekong region. Indoor farms have been researched, with actual successful test cases, since the 1980s in Japan and the United States (Kozai, Niu, and Takagaki 2016). This discrepancy calls for further research into the potential for integrated CAATs in extensive agriculture, so as to boost investor confidence in the potential of transforming this industry.

A fifth reason is inertia. The problem with extensive CAATs is the mind-set that status quo practices in extensive agriculture are acceptable, or at least acceptably suboptimal. The desire to increase yields significantly is not present. In contrast, indoor farms, with fewer legacy practices, are more open to implementing CAATs. The yield and efficiency improvements that indoor farms reap from CAATs, it is hoped, will spark the imagination of farmers and technology entrepreneurs in outdoor farming to develop similar integrated solutions that can have a positive disruptive impact on the way food insecurity is addressed. This can in turn allow for more localized solutions that respond to the specific challenges faced by farmers, because the impacts of climate change can vary depending on the extant resource conditions (such as soil type and water availability) and farming practices (such as overfertilization that causes weeds to crop up).

b. The Need to Reframe CAATs as a Private Investment Opportunity

Given the trends in environmental factors that affect crop yields, it would be logical to expect farmers, governments, and the private sector to invest in CAATs, to minimize the negative impacts of climate change on agricultural production. At a minimum, one might expect zero-sum investments, wherein the cost of investment equals the benefit of yield losses avoided over a long-term investment horizon. In the best case, investments would be made to allow crop yields to be not just maintained but even improved, making farming even more profitable and increasing returns to those who have already invested in the sector.

However, as has been observed in the Mekong countries, even zero-sum investments in CAATs are not happening, in spite of the great need for them. A common way of thinking, evident from the ERIA workshop, is that the role of governments it to put available funding to use, whereas the role of international donor and development agencies is to provide this funding.

Placing the onus on international donors and development agencies, however, is problematic because international donor agencies currently play a smaller role in capital injections into developing countries than does the private sector, especially in Asia. In development assistance recipient countries in

East Asia and the Pacific,[3] only 3 percent of international funding transfers come from official development assistance (ODA) today, whereas private-sector foreign direct investment (FDI) accounts for 97 percent (World Bank 2018). This is a significant landscape transformation in funding, compared with the situation in the 1970s, when 86 percent came from ODA and 14 percent from FDI. Given this change in the international funding landscape, more impetus can be expected from the private sector.

These facts prompt a revisiting of the role of government and an exploration of potential entry points for private-sector investment. In fact, over the past few decades, multinational private companies have already been investing in "crop solutions" that can improve the productivity of farming, such as pesticides and herbicides. An international consortium, CGIAR, focuses on developing biotechnological solutions, such as traits of heat, drought, and flood resistance. Moreover, these companies are taking pains to see that their products reach their target user markets, which are less-developed countries. What is lacking now is an integrator that (1) uses IoT technologies to make these diverse technologies compatible, and (2) can assess the potential long-term yield benefits and process the resulting data into projected returns on investments.

c. The Need for Financial Viability Assessments of Prototype IoT-Enabled Extensive Farms

Today, the UAI tool is being further developed for use in Singapore and elsewhere, to provide a better understanding of how the viability of investing in CAATs can improve (or worsen) with government policies. This can help inform policy, such as in determining how alternative property price and tax regimes may improve the uptake of CAATs, in order to make headway towards addressing interlinked objectives of food security, job creation, and contributions to national output. It is likewise being tailored for investors' use. For instance, an exploratory collaboration with Singapore's global investment company, Temasek International, as a 'test client', highlighted metrics and additional functionalities important for investors, such as the internal rate of return. The tool was also found to be useful for apples-to-apples comparisons of funding proposals by farmers/entrepreneurs in terms of productivity and profitability.

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[3] Countries in the region that receive funding from the International Bank for Reconstruction and Development and the International Development Agency.

Building on these insights, a similar platform can thus be developed to bring agriculture ministries, farmers, regional development planners, food producers, and most critically, investors together to identify the investment horizon for combinations of CAATs for extensive agriculture. This platform can be an extension of UAI, potentially referred to as RAI (RuralAgInvest), which can be co-developed with groups of technology providers whose products are compatible. Such a tool would allow for a more nuanced understanding of barriers preventing extensive CAATs from scaling up.

An important hurdle to overcome is the insufficiency of data for conducting similar viability assessments of extensive CAATs. These CAATs are mostly applied separately, in different settings, and no IoT enabled extensive farm exists in the Mekong countries yet that employs combinations of these technologies. This brings to fore the need for a ***prototype IoT-enabled extensive farm*** for the purpose of testing combinations of CAATs within a small, defined plot of land, to generate this data. This may be piloted in a specific geographic area, such as one of the critical subregions within the Mekong countries.

If the viability assessment shows IoT-enabled extensive farms to be a viable investment opportunity, it could incentivize governments to support the entry of companies that provide CAATs to farmers, as well as companies that produce the materials for developing CAATs (such as the manufacturing of drones and sensors), to locate in their countries and form an industry cluster. Healthy competition and collaboration among firms within such clusters (Porter 2008) may then lead to innovations in the technologies listed in Box 1 (Montesclaros and Teng 2018a), such as in being responsive to the unique needs of the area where the cluster is located, or in reducing the cost of providing these technologies. For instance, this mechanism could allow for identifying the optimal combination of CAATs (biotechnology, nutrient control, and control of environmental factors) to employ in a farm to maximize both yields and returns on investment.

The financial rewards that can be reaped from CAATs may likewise provide an impetus to governments to speedily address infrastructure gaps (such as telecommunications infrastructure and roads for transporting food), and inefficient market regulations (such as barriers that prevent low-cost input providers from entering, or government monopolies on the distribution of inputs). These could also convince governments to support company mergers which provide CAAT providers with better financial leverage to integrate, innovate and upscale faster.

VI. Conclusion

This discussion paper has provided multiple cases of indoor farms in which CAATs are applied integrally (rather than individually). Such integration has allowed indoor farming to become a viable investment endeavor within Singapore and globally. Aided by these technologies, in fact, the industry for hydroponics (which is practiced in indoor farms) is expected to experience a compound annual growth rate of 6.5 percent from 2018 to 2023.

Based on this insight, we have argued that a similar improvement in the viability of CAATs in extensive (outdoor) farming, especially in the Mekong countries, can be reaped if integrated CAATs are applied to extensive farms. This does not mean that there should be indoor farms in Mekong countries; rather, there is a need to replicate the principle of seamlessly linking different CAATs (sensors, crop analytics, and automation) within extensive farms to maximize the technologies' synergistic effects on crop yields, and in turn, demonstrate the viability of CAAT investment. Greater viability can potentially draw in more private-sector funding to bridge investment gaps in these countries.

In order to transfer these lessons from indoor farms in Singapore and other developed countries to extensive farms in the Mekong countries, a potential venture is to develop a ***prototype IoT-enabled extensive farm*** that integrates multiple CAATs. Extending the UAI tool, applied to indoor farms, to develop RAI, which will assess the viability of outdoor farms, can help translate such an assessment into terms that investors can appreciate. It will likewise be critical to develop marketing channels from farm to fork, to solidify the value proposition of these next-generation extensive farms.

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