Raising the stakes: cassava seed networks at multiple scales in Cambodia and Vietnam

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Abstract

Cassava is one of the most important annual crops in Southeast Asia, and faces increasing seed borne pest and disease pressures. Despite this, cassava seed systems have received scant research attention. In a first analysis of Vietnamese and Cambodian cassava seed systems, we characterized existing cassava seed systems in 2016-17 through a farmer survey based approach at both national and community scales, with particular focus on identifying seed system actors, planting material management, exchange mechanisms, geographies, and variety use, and performed a network analysis of detected seed movement at the provincial level. Despite their status as self-organized 'informal' networks, the cassava seed systems used by farmers in Vietnam and Cambodia are complex, connected over multiple scales, and include links between geographically distant sites. Cassava planting material was exchanged through farmer seed systems**,** in which re-use of farm-saved supply and community-level exchanges dominated. At the national level, use of self-saved seed occurred in 47 and 64% of seed use cases in Cambodia and Vietnam, respectively. Movement within communes was prevalent, with 82 and 78% of seed provided to others being exchanged between family and acquaintances within the commune in Cambodia and Vietnam, respectively. Yet, meaningful proportions of seed flows, mediated mostly by traders, also formed inter-provincial and international exchange networks, with 20% of Cambodia's seed acquisitions imported from abroad, especially neighboring Vietnam and Thailand. Dedicated seed traders and local cassava collection points played important roles in the planting material distribution network at particular sites. Sales of planting material were important means of both acquiring and providing seed in both countries, and

commercial sale was more prevalent in high-intensity than in low-intensity production sites. Considerable variability existed in local seed networks, depending on the intensity of production and integration with trader networks. Adapted innovations are needed to upgrade cassava seed systems in the face of emerging pests and diseases, taking into account and building on the strengths of the existing systems; including their social nature and ability to quickly and efficiently distribute planting materials at the regional level.

Introduction

Cassava (*Manihot esculenta* Crantz) is a perennial root crop originating from the tropical Americas (Nassar and Ortiz, 2009), and grown on >3.5 M ha in Southeast Asia, primarily as a smallholder cash crop serving global starch-based industrial markets (Cramb et al., 2017). From 2000-2016, Cambodia and Vietnam have both experienced rapid increases in cassava area, with planted area in Cambodia increasing 40-fold, from 16,000 to 684,070 ha (MAFF, 2017), and Vietnam registering a 2.4-fold increase, from 237,600 to 569,900 ha (GSO, 2017). In both countries the bulk of cassava roots are produced by smallholder farmers, although larger commercial plantations have begun increasing in number (Ziegler et al., 2009). Vietnamese factories predominantly process starch from fresh roots, or produce dried chips for export, while the Cambodian sector primarily exports raw materials (either fresh roots or dried chips) to neighboring Vietnam and Thailand for processing and re-export (SNV, 2015). The Southeast Asian market as a whole is driven largely by derived demand from Chinese industrial processors (Cramb et al., 2017).

Vietnam and Cambodia's cassava boom has coincided with the emergence and spread of a host of pests and diseases, including the cassava mealybug and cassava witches broom disease (CWB) (Alvarez et al., 2013; Graziosi et al., 2016). The most recent arrival is a member of the cassava mosaic virus family of geminiviruses, the Sri Lanka Cassava Mosaic Virus (SLCMV) (Wang et al., 2016). Endemic to India and Sri Lanka, SLCMV is disseminated both by *Bemisia tabaci* whitefly, and through the movement of infected planting materials (Legg, 2010). The appearance of SLCMV is part of a larger pattern of pest and disease invasion in Southeast Asian cassava (Graziosi et al., 2016), including interacting co-infections by several pest species (Wyckhuys et al., 2017). These threats to the multi-billion dollar regional industry, all transmissible by the movement of contaminated planting material, call for an increased understanding of existing cassava seed systems.

Cassava can be multiplied vegetatively from stem, meristem, leaf-bud, and root tip cuttings, or sexually from botanical seed (Danso and Ford-Lloyd, 2003; Duputié et al., 2007; Hegde et al., 2016; Rajendran et al., 2005). Southeast Asian producers use the woody ~2 m stems of mature plants for cassava propagation, chopping them into 15-25 cm cuttings immediately before planting (FAO, 2001; Howeler, 2014). With true seed playing a negligible role, stems or 'stakes' are equivalent to 'seeds' in cassava production systems (Coomes, 2010), and we use the terms interchangeably here. As in other vegetatively propagated crops, the cassava seed system is characterized by bulky planting material (Ceballos et al., 2011; Legg et al., 2014), low multiplication rates (Elias et al., 2007; Legg et al., 2014), low seed dormancy (Dyer et al., 2011), maintenance of the genetic identity of varieties as clones from one generation to the next (Ceballos et al., 2015), domination of self-regulated or 'informal' seed exchange (Coomes et al., 2015), and high potential buildup of seed-borne pests and diseases (Howeler, 2014; Thomas-Sharma et al., 2017). Planting one hectare of cassava requires approximately ~1000 kg of stakes, compared to ~25 kg / ha of maize seed (Henry, 1991), and a single cassava plant may only produce 5-10 high quality cuttings, compared to 300 seeds for maize (FAO, 2001; Ceballos et al., 2011). Annual replanting of the >1.2 M ha of cassava in Vietnam and Cambodia therefore requires a network of supply for ~1.2-1.8 Bn viable stakes, at the right time, and in the right places for planting.

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Seed network analysis, also called seed flow mapping (Tadesse et al., 2016), involves analyzing seed provision and acquisition (links) between pairs of actors (nodes) (Almekinders, 1994; Bentley et al., 2017; Buddenhagen et al., 2017). Diverse actors may be involved from the public and private sectors, while seed flows may be characterized at spatial scales including households, villages, regions, and nations (Moslonka–Lefebvre et al., 2011; Zimmerer, 2003). Seed networks can be characterized by the social categories of nodes (e.g., gender, trust, ethnicity, religion), and whether social categories influence the probability of links (dynamic or static) based on economics (e.g., involving prices and volumes), technical characteristics (e.g., based on seed categories and rates of renewal), geography (e.g., based on proximity), or disease status (e.g., infected or uninfected with a particular pathogen). Seed exchange mechanisms include sale, barter, gifts, and loans, with trade as simple as gifts between neighbors, or as complex as cross-border transactions involving intermediate actors and redistribution networks. Analysis of seed networks as potential epidemic pathways can help to identify key locations for sampling and mitigation of pathogens in seed networks, and to evaluate the roles of different actors in those epidemics (Andersen et al. 2018, Buddenhagen et al. 2017).

Seed systems are often described as being formal (e.g. registered or certified seed), informal (e.g. farmer or local seed), and mixed or integrated (e.g. quality declared seed). The weaknesses of such a rigid framework are well recognized (Coomes et al., 2015), and may promote misconceptions about system strengths and weaknesses (Thiele, 1999; Coomes et al., 2015; Urrea-Hernandez et al., 2016), particularly given the growing recognition and appreciation of mixed or integrated models facilitating smallholder access (ASF, 2016; Luby and Goldman, 2016; McGuire and Sperling, 2016; Montenegro de Wit, 2017). Here we use the terms formal and informal for simplicity, but with full recognition of their limitations.

Globally, cassava seed systems are typically informal, and managed without major public sector involvement in the production, supply, or quality control of planting materials (Elias et al., 2000; Sardos et al., 2008; Dyer et al., 2011; Legg et al., 2014; McGuire and Sperling, 2016). Until recently, serious seed-borne pests, viruses, and bacterial or phytoplasma diseases were mostly absent in the region, allowing the status quo to continue with little serious scrutiny (Legg et al., 2014; Graziosi et al., 2016). What is ‘known’ about cassava seed networks in Southeast Asia (as commonly occurs elsewhere) is often based on generalizations, isolated case studies, or anecdotal opinion, rather than systematic analysis (Dyer et al., 2011). Seed system interventions are increasingly proposed as a development focus to cope with cassava’s emerging phytosanitary challenges (Legg et al., 2014; McQuaid et al., 2016), yet it remains common for research and development of ‘clean seed systems’ to predominantly focus on single segments of the supply chain, without necessarily integrating innovations (e.g. FAO, 2010; Shiji et al., 2014; Castañeda-Méndez et al., 2017). Elucidating the structure and functioning of existing seed systems is an essential prerequisite to designing effective and impactful seed system innovations acceptable to local stakeholders.

The present study characterizes cassava seed systems in Cambodia and Vietnam at individual, community, and provincial/national scales, including the mechanisms and actors involved in seed procurement, exchange, and movement. We present a baseline assessment and provide to our knowledge the first systematic investigation of national cassava seed systems in Southeast Asia. Our specific objectives were to (i) understand farmer seed use profiles and behavior, (ii) determine the actors and mechanisms involved in seed procurement and their relative importance (including gender dimensions), (iii) characterize seed networks including the spatial reach of seed, transaction volumes, and regions of high importance, and (iv) analyze the existing policy environment.

Materials and methods

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Surveys, study site selection and sampling

Two types of stakeholder surveys were conducted: (i) two national surveys, and (ii) four detailed subnational surveys (Figure 1). National surveys covered the following themes: (a) respondent information, (b) seed use overview, and (c) field and household data. In addition to the aforementioned categories, the subnational surveys collected data on (d) quality, (e) affordability/profitability, and (f) information sources, and conducted follow-up surveys with local traders identified by respondents when possible. Participants in the subnational surveys were also asked about seed purchase and amount spent on seed over the past three seasons.

The national surveys were conducted during November and December 2016, combined with a parallel study evaluating SLCMV incidence. Sampling methods were based on previous studies monitoring cassava mosaic virus outbreaks in Africa (Sseruwagi et al., 2004; Legg et al., 2011). For the national surveys, 15 districts per country covering the areas of highest cassava production were selected (Fig. 1). An additional 16th district, Koun Mom in Ratanakiri province, Cambodia, was added (the site of first detection of the recent SLCMV outbreak in Southeast Asia) (Wang et al., 2016). In both countries, district selection was adjusted with the input of local expert authorities. Within each selected district, 15 approximately equidistant fields were selected along the primary motorable road. For each selected site, respondents were asked to identify the household member most responsible for cassava production activities; this individual was then interviewed.

Surveys were conducted by trained enumerators supported by local authorities (in Cambodia the General Directorate of Agriculture, supported by Provincial Department of Agriculture, Forestry, and Fisheries; in Vietnam the Plant Protection Department and the Plant Protection Research Institute) in Khmer and Vietnamese, and included the following sample sizes: (1) Cambodia: n=240 (16 districts), (2) Vietnam: n=206 (15 districts).

For the four subnational surveys, one high-intensity cassava production site and one low-intensity site were selected in each country. High-intensity production sites were defined as well-established, high density cassava producing districts, while low-intensity production sites had lower cassava density. The selection of these districts was based on planted area timeline series where available, supplemented with information from local experts and authorities. Target communes within selected districts were chosen based on expert advice from national implementing partners (Tay Nguyen University for Dak Lak, Hung Loc Agricultural Research Center for Tay Ninh, University of Battambang for Battambang, and Royal University of Agriculture for Ratanakiri).

In Vietnam, the border of Tan Hiep and Tan Hoi communes, Tan Chau district (pop. 106,264) (GSO, 2017) of Tay Ninh province was selected as a high-intensity site. Ea Sar commune of Ea Kar district (pop. 142,525), Dak Lak province was selected as a contrasting low-intensity site. In Cambodia, the high-intensity site was spread across 4 communes on the border of Banan (pop. 92,138) and Rotanak Mondul (pop. 41,170) districts in Battambang province, while Trapeang Chres commune, Koun Mom district (pop. 15,505), Ratanakiri province, was selected as the low-intensity site. Respondents within communes were randomly selected within a 5km sampling radius, aiming for high completeness. Subnational surveys were conducted in February and March, 2017, and included the following sample sizes: (1) Cambodia, Battambang: n = 100, (2) Cambodia, Ratanakiri: n = 100, (3) Vietnam, Tay Ninh: n = 100, (4) Vietnam, Dak Lak: n = 94. To gather information on trader activities and characteristics, enumerators attempted to contact all traders identified by respondents of the four subnational surveys for follow-up trader interviews. For the purposes of this study, traders were defined as those specializing in mediating exchange of planting materials beyond their own

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needs and supply. Transactions here refer to all sources of seed contributing to the farmer's seed supply (acquisition), and seed provided to others (provision).

Data analysis

All information was recorded on paper questionnaires, translated from Khmer or Vietnamese to English, digitized, and analyzed using R (R Core Team, 2017). Maps were created in ArcMap 10.3 and R. Seed transactions of different types among categories of actors at the 4 subnational sites were visualized using parallel sets, and Fruchterman-Reingold plots were used to visualize seed exchange among individual respondents (Supplementary Material 2). To characterize regional seed flows, national survey data was aggregated to province level. Nodes in the estimated network represent surveyed provinces as well as non-surveyed provinces that were designated as seed 'sources' or 'sinks' by survey respondents. In cases where finer-scale seed source providences were not reported, transactions were aggregated to country level. Links represent aggregated stake transactions between nodes (provinces or countries). To account for differences in sample sizes between surveyed provinces, link weights were calibrated by dividing the total number of stakes by the number of farmers surveyed in the "source" province. Link weights were thus the estimated number of stakes exchanged per household. Note that the nature of the survey allows seed movement to be estimated only in certain directions. For example, the role of Thailand and Laos in the network were only evaluated in terms of reported seed movement from these countries into Vietnam and Cambodia, while reported seed movement to, from, and within Vietnam and Cambodia was analyzed in depth. Transactions were aggregated in an adjacency matrix to construct a network graph with provinces as nodes, and seed exchange as links. To understand the role of provinces as net "importers" or "exporters", node in- and out-strength were calculated as the sum of the volumes of incoming and outgoing stakes from each province (not including self-loops). Network statistics, such as node degree, were also calculated to understand the role of provinces in the seed exchange network. Network analysis was conducted and visualized in R, using dplyr (Wickham and Francois, 2016), igraph (Csárdi, 2006), and custom R code.

Policy review

A review of existing policy was conducted to identify (a) key legislation, (b) key stakeholders, and (c) seed certification categories applying to vegetatively propagated crops in both Cambodia and Vietnam (after Tun et al., 2015).

Results

Socioeconomic and basic production characteristics

National surveys:

In Cambodia 21% of respondents (those identifying as mainly responsible for cassava cultivation activities) were female, while in Vietnam 24% of respondents were female. Overall, farmers in Vietnam had more experience growing cassava (12.8 ± 9.5 years) than their Cambodian counterparts (6.3 ± 5.0 years). The cassava value chain in both countries is industry-oriented; none of the survey respondents reported producing cassava to be eaten domestically. For farmers in both countries cassava is a major cash crop, generating on average about half of their reported household-level income.

Average farm sizes in Cambodia were 3 times larger than those in Vietnam (6.4 ± 9.0, n=206, versus 2.0 ± 2.5, n=240 ha, respectively). Similar differences were observed for farm area dedicated to cassava; 3.9 ± 5.6 ha in Cambodia versus 1.4 ± 1.3 ha in Vietnam. The use of fertilizers was much

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lower in Cambodia (14.2%) than in Vietnam (73.1%). Pests and diseases were often mentioned as being current problems in Cambodia (75%), and less so in Vietnam (45%). Pesticide use was high in Cambodia (78%) and Vietnam (89%), but products used were commonly not known to the farmer, and included a diverse array of mentions of herbicides, insecticides, and other compounds.

Cassava varietal diversity managed by individual households was low, with most households describing maintaining a single variety per farm in both countries (Table 1). In Vietnam the average number of varieties reported per household was 1.1 ± 0.3, with a maximum portfolio of 3 varieties, while Cambodia averaged 1.4 ± 0.6, with a maximum portfolio of 4 varieties. However it was clear across the survey sites that farmers had difficulty distinguishing varieties and often could not provide a name at all. Additional farm characteristics are presented in Supplementary Material 1.

Subnational surveys:

In Cambodia, 26% of respondents were female in Battambang and 47% were female in Ratanakiri. In Vietnam, 10% of respondents in Tay Ninh were female, while 49% of respondents were female in Dak Lak. The number of years of cassava-cropping experience equally varied: 2.7 ± 1.4, 3.2 ± 1.9, 10.3 ± 6.5, and 7.6 ± 3.8 years per household in Battambang, Ratanakiri, Tay Ninh, and Dak Lak, respectively. The four sites were similar in terms of household size (4.7 to 5.5 members), and number of household members involved in full-time farming (2.16 to 2.93). In Cambodia, harvested roots were primarily sold to traders (41%) or collection points (55%). In Vietnam, 8% of respondents indicated selling their roots to collection points, while 53% sold to traders and 42% sold directly to factories. Participation in more than one root value chain was rare.

The total size of cropped land per household in Dak Lak (2.6 ha ± 2.5) was about half of that in the other three sites (5.6 ± 6.3; 5.5, ± 4.4; and 5.5 ± 11.3 ha in Battambang, Ratanakiri, and Tay Ninh, respectively). The average areas dedicated to cassava per household were variable: 3.4 ± 4.0, 2.4 ± 1.8, 4.3 ± 9.8, and 1.6 ± 2.0 ha per household in Battambang, Ratanakiri, Tay Ninh and Dak Lak, respectively. The variability in these values reflects the inclusion of some particularly large farms, in both countries found in the high-intensity production sites, with maximum cassava areas of 40 ha in Battambang and 75 ha in Tay Ninh. Between 94 and 100% of respondents indicated that a neighboring field was growing cassava, demonstrating the near-contiguous nature of the cassava landscape in Vietnam and Cambodia's key production zones.

High levels of pesticide use were reported (>80% in both Cambodian sites; ~60% in both Vietnamese sites), although the names and ingredients of the products used were typically unknown, with colloquial or generic descriptive terms often employed, including the color of the product bottle, or the specific insects or symptoms farmers wished to eliminate. The use of insecticide was noted in 17, 51, 56, and 34% of cases in Battambang, Ratanakiri, Tay Ninh, and Dak Lak, respectively. In Ratanakiri alone, termiticide was singled out by respondents as a separate category, and its use mentioned by 41% of respondents.

Across the four study sites, between 81 and 95% of respondents specified that they intended to continue growing cassava in the following season, despite changes in global markets resulting in low cassava prices during the study year. All four sites were characterized by low varietal diversity (Table 1). Frequency of seed purchase over the three previous cropping seasons differed between the four sites (Table 2). In each of the three seasons, a lower percentage of farmers in Dak Lak and Ratanakiri (7-10 and 14-19%, respectively) purchased planting materials, compared to Battambang or Tay Ninh (22-30 and 33-63%, respectively). The average amount spent on stakes was also lower at the former two sites. Total average price paid was reported, rather than calculated amounts

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proportional to farm area, due to many factors, including changing land sizes over the 3 year period, variable partial and whole replacements of seed supply, and fluctuating seed prices.

Seed network actors

National surveys:

At the national level, farmers' own saved seed was the most frequently used seed source (Table 3). In Cambodia 39% of respondents used exclusively their own saved seed, 35% used exclusively an off-farm source, and 26% used seeds from a combination of sources. In Vietnam 63% of farmers used exclusively their own farm saved seed, 30% used exclusively an off-farm source, and only 7% used a combination of sources.

After farm-saved seed, other farmers within the community known by the respondent were the most common source of seed in both countries, making up a further 26 and 20% of seed used in Cambodia and Vietnam, respectively. Both countries had smaller numbers of transactions with farmers outside their communities (4% in each case) and other farmers they did not know (3% in Cambodia and 1% in Vietnam). In Cambodia traders played a significant role as providers of seed (18%), while in Vietnam they were less common (3%). In Vietnam 6% of seed originated from agroinput dealers and 1% from local government, while in Cambodia starch factories (1%) and local markets (1%) were mentioned.

Farmers in both countries overwhelmingly provided stakes to other farmers within their own communities. In Cambodia 82% of seed provisions to others were directed to other farmers the respondent knew within the community, and the remaining 18% were to farmers that the respondent did not know (Table 3). A frequently recurring note interviewers made for these transactions were that after cassava harvest, when there is a surplus of stakes left in the field, these latter farmers passed by the household and asked for stakes. In Vietnam, provision of seed to farmers within the community that the respondent knew were responsible for 78% of provision interactions, while 13% were to farmers the respondent did not know. In Vietnam 9% of provision transactions went to traders, compared to none in Cambodia.

Subnational surveys:

As in the national surveys, farmer-farmer exchange dominated transactions at the subnational sites. Traders were involved in < 3% of seed transactions in all sites, with the exception of Tay Ninh, where 36% of exchanges involved traders, and 13% of farmer seed acquisition transactions involved a community collection point (Table 3). Seed exchanges involving government and private industry actors (eg. starch factories), only occurred at low frequency in Dak Lak, while in Battambang 3 individuals mentioned buying stakes at a local market.

At Cambodian sites, household decisions on the acquisition of stakes were made jointly by both the male and female heads of household in 70% and 67% of cases in Battambang and Ratanakiri, respectively (see Supplementary Material 1). In Vietnam, in Tay Ninh, 73% of respondents indicated that male household heads alone were responsible for making these decisions. In Dak Lak, decisions were made equally by the male household head alone, female household head alone, and both together, with each category bearing approximately a third of responses.

In both of the low-density sites, most farmers relied on self-saved seed, but also interacted frequently, exchanging seed with multiple others in the community, while traders were more rare (Fig. 2). In Battambang, farmers saved their own seed less than in the low-intensity sites, exchanged mostly with each other, and when they did they relied on few exchange partners. Tay Ninh is dominated by a

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large number of trader interactions, with some farmers interacting with multiple traders and some traders being identified by multiple respondents.

In both of the high-intensity sites responsibility for cassava cropping was dominated by men, while the low production intensity sites reported gender involvement approaching parity (Fig. 2). At all sites, women's contribution to the total number of seed acquisitions from others approximated their gender proportion in the total sample. Relative to their proportion in the sample, women were slightly underrepresented in provision of seed to others in Cambodian sites, while in both Vietnamese sites they contributed slightly more than men.

Seed supply and provisioning mechanisms and volumes

National surveys:

A total of 849 seed provision and acquisitions were recorded in the binational survey (survey n = 446). In both countries farm-saved materials were a predominant source of seed (Table 3), accounting for 47 and 64% of seed used in Cambodia and Vietnam, respectively. In addition, 71 and 84% of respondents indicated that they intended to re-use the current year's seeds in the following season in Cambodia and Vietnam, respectively. However, in Cambodia particularly high rates of seed purchase were observed (43% of seed use), followed by gifts (10%). Conversely, in Vietnam a lower percentage of stake purchases was reported (15%) and gifts were more common (13%), while a further 7% of acquisitions were listed as exchange/barter transactions (Table 4).

Over all stake acquisitions recorded, omitting self-provided seed, the average numbers of stakes per acquisition were 8583 ± 17761 in Cambodia and 1927 ± 2513 in Vietnam. Over all recorded stake provisions to others, the average numbers of stakes exchanged per provision were 7261 ± 18764 in Cambodia and 5443 ± 12162 in Vietnam.

Subnational surveys:

A total of 660 seed provision and acquisitions were recorded in the subnational surveys (survey n = 394). In 2016, this averaged 1.56 seed transactions per respondent in Battambang, 2.01 in Ratanakiri, 1.34 in Tay Ninh, and 1.81 in Dak Lak. Most farmers filled their 2016 off-farm seed requirements exclusively through interactions with only a single source. The most common strategy was re-use of own farm-saved seed in Battambang, Ratanakiri, and Dak Lak (59, 69, and 87% of respondents, respectively). Conversely, in Tay Ninh only 30% of farmers relied on self-saved seed alone. The use of sources other than farm-saved seed occurred in 66% of farmers in Tay Ninh, 13% in Dak Lak, 39% in Battambang, and 21% in Ratanakiri.

Most farmers (between 79-93%) planned to re-use their seed in the next season, except for farmers from Tay Ninh, of whom only 11% intended to re-use their current seed material. The other high production intensity site, Battambang, indicated the opposite, with 93% of planting materials destined for re-use on the same farm. The use of seed from more than one type of seed source was uncommon at all sites (4, 0, 2, and 10% in Tay Ninh, Dak Lak, Battambang, and Ratanakiri, respectively). In the most remote site, Ratanakiri, 10% of respondents indicated using a combination of their own stakes and other acquisitions.

Use of farm-saved seed in the low-intensity sites represented 74 and 86% of the total number of seed acquisitions in Ratanakiri and Dak Lak, respectively, and 64 and 32% in the high-intensity sites of Battambang and Tay Ninh, respectively (Table 3). Exchanges of planting materials between farmers were common at all sites, although the nature of these exchanges varied. At high-intensity production sites in both countries, sale was a more common mechanism of seed acquisition than at the low-intensity sites. Tay Ninh was the only site in which purchase of materials was more frequent than

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353 farm saved seed, with the major sale supply actors being traders, other farmers, and community root
354 collection points (Fig. 2).

355 Seed provisioning to others through sale was more common in high-intensity sites than in their low-
356 intensity counterparts, ranking as the most important mechanism of provisioning at both high-
357 intensity sites. Within both high-intensity sites, the majority of farmers' seed provisions to others
358 were sales (57% of transactions in Battambang and 79% of transactions in Tay Ninh), while at low-
359 intensity sites gifts remained the dominant mechanism of provision to others (54% in Ratanakiri,
360 93% in Dak Lak) (Table 4). Figure 2 illustrates that stakes sold to others were mostly destined for
361 traders in Tay Ninh, while in Battambang other farmers were the main purchasers.

362 Over all stake acquisitions recorded (omitting self-provided seed), the average numbers of stakes per
363 acquisition were 6265 ± 5132 in Battambang, 1820 ± 2542 in Ratanakiri, 8281 ± 12201 in Tay Ninh,
364 and 2719 ± 1794 in Dak Lak. Over all recorded stake provisions to others, the average numbers of
365 stakes per provision were 5289 ± 6437 in Battambang, 2608 ± 4428 in Ratanakiri, 39100 ± 70066 in
366 Tay Ninh, and 3312 ± 4816 in Dak Lak, respectively.

367 ***Spatial reach of seed networks***

368 National surveys:

369 Table 5 describes the geographic distances involved in recorded seed exchanges. Most of the seed
370 transactions observed were over short distances. In both countries, most seeds originated from within
371 the commune; 71 and 90% of individual acquisitions in Cambodia and Vietnam respectively. In
372 farmer provision of stakes to others, 91 and 87% in Cambodia and Vietnam respectively were within
373 the same commune. However, a significant number of farmers did indicate exchanging seeds outside
374 of their communities.

375 In Cambodia international sources of seed were mentioned in 76 cases (20% of individual
376 acquisitions), while no such cases were reported in Vietnam. These included imported planting
377 materials into Cambodia, in descending order of frequency, from Vietnam, Thailand, and Laos.
378 Acquisitions originating from other provinces within the country involved 2 and 4% of seed use in
379 Cambodia and Vietnam. In Vietnam no farmers reported providing seed to buyers outside of the
380 country, but 12% of seed provisions to others were instead reported as being to 'unknown'
381 destinations, with traders implicated as the buyers.

382 Due to the degree of uncertainty in locations of stake origin/destination, we were unable to calculate
383 seed travel distances and report our results here on the order of communes, districts, provinces and
384 countries; all of which vary in size. However the longest distances observed were those between
385 Vietnam and Cambodia's Western provinces (in particular Battambang, Banteay Meanchey, and
386 Oddar Meanchey, all of which are between 250 – 350 kilometers from the Vietnamese border.

387 Subnational 'in-depth' surveys:

388 The majority of farmers both acquired and provided most stakes within their own communes: 86 and
389 73% in Battambang, 97 and 62% in Tay Ninh, 95 and 91% in Ratanakiri, and 86 and 95% in Dak
390 Lak, respectively.

391 In the low-intensity sites of Ratanakiri and Dak Lak, 91 and 95%, respectively, of seed provisions to
392 others were within the commune, and the absolute number of exchanges was higher than in high-
393 intensity sites. At the high-intensity sites, only 73 and 62% of seed provisions remained within the
394 commune in Battambang and Tay Ninh, respectively, with significant amounts of exchange taking
395 place at higher geographic scales (Table 5).

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In Tay Ninh 28% of stake provision transactions went to 'unknown' destinations; far more than in the other 3 sites. Tay Ninh also received and provided a greater proportion of seed transactions in other communes within their district (3 and 10%, respectively). The highest percentage of seed acquisition from other provinces within the same country was in Dak Lak (7%).

National survey seed network analysis

National-level survey data included 840 unique transactions (both seed acquisitions and provisions) recorded from 31 districts in 26 Cambodian and Vietnamese provinces in 2016. Cambodia exhibited a high degree of interprovincial exchange (Figure 3a), including non-monetary transactions and several cases of long-distance trade (e.g. between Oddar Meanchey and Stung Treng). By contrast, Vietnam exhibited less exchange overall, with exchanges often barter-type transactions within provinces (< 10,000 stakes per farmer, Figure 3a). Many Cambodian farmers reported receiving stakes internationally from Vietnam, Thailand, and Laos, although they were usually unable to provide a province of origin (Figure 3, gray dashed lines). Within five of the Cambodian provinces surveyed (Battambang, Pailin, Banteay Meanchey, Tay Ninh, and Tboung Khmum), very large volumes of stakes were exchanged between farmers within these provinces (>10000 stakes per farmer in some cases).

In the provincial exchange network, the Cambodian province of Battambang had the highest node degree (6), with connections to several other Cambodian provinces, as well as traders in Thailand and Vietnam. Battambang also had the highest eigenvector centrality, meaning that it is not only highly connected, but also connected to other highly connected neighbors. This may in part be driven by the comparatively large area of cassava in Cambodia's Northwestern provinces. Battambang also exhibited both the highest node in- and out-strength, importing only a slightly higher number of stakes than were exported (Figure 3b). The Cambodian provinces of Pailin, Kampong Thom, and Oddar Meanchey also had similar hub-node properties. From the data captured in this survey, provinces were characterized as net-importers or exporters based on their node-strength (Figure 3b). It is important to note that it was difficult to capture exchanges made between intermediate traders, for example, a large number of transactions were provided to traders in Tay Ninh (Table 3), but their final destinations were unknown (Table 5), meaning that the respondent did not even know which country they were destined for, and these transactions are therefore not represented on the final figure (Figure 3b). This limitation seriously underrepresents the significant role of Tay Ninh as an exporter of seed to Cambodia and other Southern Vietnamese provinces.

Planting material handling and quality

Planting stakes are stored in bundles of 15-25, kept either in the open field or underneath trees on the field borders. Formal seed production, certification, and marketing are virtually non-existent in this region. The percentages of respondents applying chemical treatments to their stakes to prior to planting were 20 and 24% in the high-intensity production sites of Battambang and Tay Ninh, respectively, and 76 and 30% in the low-intensity sites of Ratanakiri and Dak Lak, respectively. At both Vietnamese sites the most common practice mentioned was use of a chemical product bath shortly before planting the stakes, while in Cambodia applying a chemical product during storage or using a combination of both practices was more common.

Loss of stake viability during storage occurred in 85 and 80% of households in Battambang and Ratanakiri, with loss estimates of 27 and 32% of stored seed, respectively. In Vietnam, loss of seed viability during storage occurred in 32 and 64% of households in Tay Ninh and Dak Lak, with loss estimates of 25 and 27% of stored seed, respectively.

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Over all 1462 seed transactions recorded in both surveys, only 1% of transactions were rated by farmers as containing poor quality stakes. At the national level, most farmers in Cambodia and Vietnam considered that the stakes they acquired were of good or average quality (67 vs 30% and 82 vs 18%, respectively), and that planting materials they provided to others were of good and average quality (85 vs 15% and 66 vs 32%, respectively). Quality is a subjective measure, and farmer perceptions in the present study were related to a variety of quality indicators, including, in descending order of importance, number and density of nodes (ie. axillary bud/leaf scar), stake size, age/freshness of planting materials, pest and disease symptoms, and a handful of other characteristics (Figure 4). Number/density of nodes, followed by size of stakes, were the most commonly mentioned indicator of quality at all of the subnational sites except Dak Lak, in which the order was reversed. Freshness/age of stakes and signs of pest and disease were the third and fourth most commonly mentioned quality indicators.

Traders

In the vast majority of cases farmers indicated that they did not have contact information to reach stake traders, frequently stating that they were not based in the community. Tay Ninh was the exception to this rule, identifying interactions with over 30 individual traders in the 2016-17 season. Only a small number of traders were successfully contacted and interviewed in Tay Ninh (n = 12), and Dak Lak (n = 7), while in Cambodia only a single trader was contacted; the sole trader serving the study commune in Ratanakiri province. Consequently the traders who were interviewed were also typically those who were based in the communities. In Cambodia, the single trader contacted was a female shop owner who had bought stakes from neighboring Kampong Cham province, but noted that the stakes had first entered the community via another trader from Vietnam.

In Tay Ninh, all traders interviewed were male, although in two cases the respondents indicated that their wives were also involved in the business of stake trade. In Dak Lak, 2 of the 7 traders were female. In Tay Ninh all traders indicated also farming cassava themselves, while 10 of the 12 additionally traded fresh roots; however all traders listed stake trading as their main economic activity. This contrasted sharply with Dak Lak, where six of the seven also traded fresh roots, four listed stake trading as their main activity, and only two of the seven traders were engaged in farming themselves. None of the traders in Tay Ninh reported supplying credit services to their customers, while conversely all of the traders in Dak Lak reported that they did.

All traders in Dak Lak acquired their stakes from a single source in the survey year, except one who listed two sources, and all of the suppliers of stakes were farmers that the trader knew personally. In Tay Ninh all traders purchased from multiple sources, with one trader reporting eight different sources within the single season. All traders mixed stakes together when they acquired them from multiple sources.

Traders from Tay Ninh reported selling to 15-20 farmers in the previous season, while those from Dak Lak served from 20-120 farmers. Six of the 12 traders from Tay Ninh indicated that they traded stakes into Cambodia themselves, or sold stakes at the Chang Riec border gate into Cambodia, while the remainder of their sales were within Tay Ninh province. By contrast, all stakes sold by the traders in Dak Lak originated in Tay Ninh province. Traders operating in Dak Lak all sold within their own province, with the exception of one who sold to two neighboring provinces, and another who sold to Cambodia.

Policy environment

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In Cambodia and Vietnam, the basic policy instruments to guide the development of formal seed systems are in place (Table 6). These include delegation of responsibility for various aspects of seed production and certification to organizations, and distinction of recognized seed certification classes. However, regulations are not commonly applied to cassava seed production, distribution, and reuse of planting materials, all of which predominantly occur outside the sphere of formal seed systems. Legislation is more consistently applied to rice, maize, and commercial vegetable seed value chains, and generally lack implementation on vegetatively propagated crops.

Discussion

Seed system actors in Cambodia and Vietnam

Our evaluation of the constituents and character of Cambodia and Vietnam's cassava seed systems in the present study was limited by our sample selection, which favored the important cassava-producing regions of both countries, and our results should be interpreted in that light. Similarly, due to the relative paucity of systematic research on the topic in Southeast Asia, many of the comparative studies contextualizing our findings are drawn from outside of the region. Our study provides a first situational analysis of the cassava seed systems in Cambodia and Vietnam.

Cassava seed systems in both Cambodia and Vietnam were predominantly farmer-led, with formal actors and marketing structures rarely mentioned. Prevalent use of self-supplied seed, pronounced reliance on social networks for exchange, and a near absence of agro-dealers in the supply chain are common in vegetatively propagated crops (McGuire and Sperling, 2016). Government participation was rare in our study, and we found no involvement of the NGO or relief programs found in other developing country contexts (eg. Longley and Sperling, 2002; Dyer et al., 2011; Legg et al., 2014; Christinck et al., 2018). Private sector involvement was modest and localized; agro input dealers were involved in seed supply at the Vietnamese national level (6% of seed use), a local starch factory contributed in Dak Lak (4% of seed use), and community-based cassava root collection businesses were important suppliers in Tay Ninh (13% of seed use). Private sector involvement was even rarer in Cambodia, with isolated mentions of participation of starch factories or market sellers. A similar lack of formal marketing structures was described in Amazonian cassava seed systems, where local exchange of planting materials through gifts among kin groups dominated seed exchange (Elias et al., 2000; Coomes, 2010), with preferential exchange dynamics among different kin groups and within households (Delêtre et al., 2011; Violon et al., 2016).

Social relationships and norms influence the exchange of seed at local scales (McGuire, 2008; Thomas and Caillon, 2016), and implications for social prestige related to providing or receiving seed may modify exchange patterns. The most important exchange actors in our study were friends, neighbors, and relatives, however provision of seed to strangers approached a fifth of all seed provisions in Cambodia. Farmers provided seeds to strangers at all of the subnational sites, but only reported acquiring seeds from a stranger themselves in Tay Ninh (2% of seed use cases). Coomes (2010) noted that cassava producers in Peru consistently better remembered who they had acquired seed stock from than who they had given it to, while in other cases farmers have been noted to be reluctant to 'beg' for seed from their neighbors (Samberg et al., 2013). The role of seed in social standing may have similarly influenced our respondents.

Traders were important providers of seed to farmers in both countries, and buyers of seed in Vietnam (9% of national sales, 69% in Tay Ninh), mediating seed exchanges over distances up to several hundred kilometers, in large volumes requiring coordinated logistics. The inability of survey teams to reach all but a single trader listed by Cambodian farmers for follow-up interview is a reflection of the

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highly mobile and seasonal character of trading activities, similar difficulties to those documented in interviewing sweet potato vine traders in Uganda (Rachkara et al., 2017). Traders in Vietnam's Dak Lak and Tay Ninh provinces had different business models. Only a third of Dak Lak's traders were farmers themselves, half viewed cassava seed trading as their main business, and all offered diversified services (such as supplying credit and trading fresh roots). Tay Ninh's stake traders, all themselves farmers based in the community, listed stake trading as their main business. These differences also have impacts on relationships and trust with clients. Traders operate in ever more precarious legal spaces (Wattenem, 2016), and their interactions with farmers take many forms, from systematic and recurrent to intermittent and opportunistic. The roles of cassava seed traders across different contexts remain poorly characterized, and major findings of the present study include the recognition of their importance in connecting spatially disparate seed networks, and the urgent need for further research elucidating their activities.

Existing seed networks at multiple scales

National scale

Farmer reliance on self-saved seed, frequent exchange within local communities, and facilitation of long-distance exchanges through traders depict a combination of self-contained seed reproduction, extensive decentralized short distance exchanges through commune-level interactions (including both financial and social motivators), and inter-provincial/international connectivity and exchange driven by farmer demand for seed, and industry demand for roots. This system is shaped at the regional level by a source-sink relationship between Vietnam/Thailand and Cambodia, and is likely facilitated by existing commodity transport networks.

The exclusive use of self-saved seed (39 and 63% in Cambodia and Vietnam, respectively), was less than that reported in other contexts with commercial value chain-linked production (83% of cassava producers across 12 Caribbean countries (Ospina et al., 2016)). Farmer-to-farmer seed exchange in both Vietnam and Cambodia supported decentralized distribution of stakes, with approximately a quarter of seed acquisitions and 91 and 87% of seed provision to others occurring within the respondents' own communes in Cambodia and Vietnam, respectively. The motivations and environmental and social factors influencing decisionmaking at the household and commune scales merit further inquiry.

Transactions between districts and provinces occurred at lower levels ($\leq$ 5%), typically involving trader intermediaries. Inter-province exchange was relatively uncommon in Vietnam, with transactions recorded between only a few sets of Southern neighboring provinces. Province-province exchanges were more frequent in Cambodia, especially involving the Northwest provinces of Banteay Meanchey, Oddar Meanchey, Pailin, and Battambang, Cambodia's major cassava production belt. Tay Ninh in particular played a key role in export of planting material via traders, although many of these exchanges are not represented in our network analysis due to their origins and/or destinations being unknown to the farmer respondents. These unknown interactions reached 12% of seed provisions by Vietnamese farmers to others through traders or village root collection points. Our province-province exchange network thus likely underestimates actual exchange at larger scales typically requiring trader mediation.

On a regional level, movements of large quantities of seed from Vietnam and Thailand into Cambodia are regular, involve volumes reaching millions of stakes per season, and mirror industrial root transport. Cambodia was a net sink of seed, recording no outgoing international trade. Stakes from Vietnam were imported to nine different Cambodian provinces, including those near to the Vietnamese border and also Cambodia's Northwestern provinces, > 250 km away. In addition to

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significant trans-border exchange, all trader respondents interviewed in Dak Lak reported obtaining their seeds from Tay Ninh, suggesting further inter-province trader movement in Vietnam not recorded in our farmer surveys due to the limitations of our sampling design.

Drivers of seed exchange at the inter-provincial and regional scales include cassava cropping area expansion, and the availability of inexpensive backfreight shipping from cassava root and chip trading networks. These effectively subsidize long-distance transport in a mirror image of root flows to Vietnam and Thailand's processing centers. The department of agriculture and rural development (DARD) of Tay Ninh has identified 68 cassava processing factories in Tay Ninh province with a capacity of 166,000 tons per month, drawing on fresh root supply from a large surrounding area in both Vietnam and Cambodia (DARD, 2018). DARD estimates 3.5 million tons of fresh roots were processed in these factories in 2017, of which 1.6 million tons originated in Cambodia, presenting an enormous annual flow of trucks with backfreight potential for seed transport.

Southeast Asia's climatic heterogeneity is an additional driver for regional stake exchange. In Vietnam's Northern highlands, cold, wet winters constrain production to approximately 10 months of the year, while Southern Vietnam's more regularly distributed temperature and rainfall patterns permit staggered planting. Northwest Cambodia's hot, dry cassava production belt faces important losses of seed viability from premature sprouting or desiccation during the ~3 month dry season. Stakes stored for 90 days under similar conditions in central Thailand suffered germination losses of 71% under full sun, and 56% stored under shade (Sinthuprama and Tiraporn, 1986). In the present study, seed loss was experienced by 80-85% of Cambodian respondents at the subnational sites; far more than in Vietnam (32 and 64% in Tay Ninh and Dak Lak, respectively). In Indochina, processing factories frequently offer higher prices for off-peak root supply, incentivizing early harvest, and further extending stake storage times (and hence losses). When chip markets are involved, sufficient time is needed for chopping roots (often done manually) and sun drying chips, similarly extending storage times.

Low intensity sites

Ratanakiri, the lowest production intensity site in the study, was isolated from seed exchange with other provinces, with only a single resident trader. The large imports of stakes from Vietnam detected in the national survey were not replicated in the subnational survey, in which only 2% of seed purchases were reported from traders, highlighting the variability at different locations within a single province or district. Fine-scale factors such as proximity to major root product transport routes may greatly influence the frequency of chance interactions with transient traders.

Vietnam's low-intensity site, Dak Lak, was the most farmer-dominated exchange system of the four case studies. The use of farm-saved seed was prevalent (86%), and the site had the highest absolute incidences of provision of seeds to others (n=73). These were almost exclusively through gifts, and 96% of the recipients of these interactions were other farmers. Dak Lak alone listed loans/credit as methods of acquisition and provision of stakes, and mentioned a diverse range of actors, including local government and a starch factory, as sources of stakes. Trader interactions were rare in the subnational surveys (2 and 1% of acquisitions and transactions, respectively), and in the results of the national survey Dak Lak is isolated from the remainder of the network but exhibits significant intra-province exchange. However interviews with local traders indicated frequent importation of seed from Tay Ninh province. Low-intensity sites also harbored the highest rates of accessing multiple seed sources, particularly reliance on self-saved seed and seed from acquaintances within the community (Fig. 2). Provisions of seed to others, mostly farmers within the community, were also more common at these sites.

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High intensity sites

Sales of seed were more important components of both acquisition and provision at high-intensity sites than their low-intensity counterparts. Seed provisions from high-intensity sites were primarily sales, while at low-intensity sites gifts were most important. Average volumes of stakes per provision at high-intensity sites were 2.0 times greater in Cambodia and 11.8 times greater in Vietnam than at low-intensity sites. High-intensity production sites had on average 1.4 and 2.7 times the area of cassava per household as their low-intensity counterparts in Cambodia and Vietnam, respectively, yet also recorded far fewer stake provisions to others. When they did provide planting materials to others, farmers in high-intensity production sites were more likely engage in high-volume sales, and a lower percentage of exchanges were within the commune compared to low-intensity sites (Figure 2). These trends suggest a commodification of seed supply in higher production intensity environments, where financial incentives drive high-volume, longer-distance transactions mediated by trader agents or larger landholders.

Battambang, Cambodia's largest cassava producer in 2016, recorded the highest volumes of seed movement in our study, with flows exceeding 100,000 stakes from both Thailand and Vietnam. Trade with neighboring Cambodian provinces of Kampong Chhnang, Pailin, and a large volume of intra-provincial exchanges exceeding 1 million stakes were reported. The demands of Thai and Vietnamese processing markets have led many farmers to adopt early harvesting practices due to favorable off-peak prices, extending the operational season of starch processing facilities. Battambang exhibited high rates of stake purchase over the previous three seasons (22-30% of respondents), paying the highest amount on average for seed from 2014-16, and engaging in an abundance of economic seed transactions. This led to its high connectivity in the trade network on the regional scale (Figures 3a and 3b), including a small number of transactions attaining ~300 kilometers from Vietnam into Western Cambodia.

As a province, Tay Ninh appeared largely self-contained in terms of stake exchange. As the subnational survey would reveal, this masked the large quantity of transactions with 'unknown' destinations brokered by the province's extensive trader network, and a large quantity of stakes imported into Cambodia likely originate there. Over 30 individual traders were listed by the 100 subnational survey respondents, and Tay Ninh displayed the highest rates of stake purchase (33-63% of respondents from 2014-16). In addition, 55% of seed used in the study year was purchased, and only 11% of respondents indicated planning to save their stakes for the coming season. Trader supply and purchase of stakes exceeded that of any other external actor, unique among sites in our study (Figure 2). Many farmers acquired new stakes annually from a trader in pre-arrangements in which the trader supplied quality seed, and farmers reciprocated harvest rights to their mature fields (including both roots and stems). By this arrangement, farmers avoided the labor and logistic complications of harvesting and storing large amounts of perishable planting materials. Trust-based relationships between farmers and seed traders are critical in both formal and informal seed networks (Lyon, 2000; Bentley, Van Mele, and Reece, 2011), and merit further study in Southeast Asian cassava systems.

Varietal diversity

Our survey found low varietal diversity, with a range of 1-4 varieties (avg. 1.38 in Cambodia, 1.09 in Vietnam). Similar recent findings have been reported from neighboring Thailand, where a study of 80 farms reported that 51 grew ≥2 varieties, while only 14 grew ≥3 varieties; nearly all of which were modern elite genetic lines (Fu et al., 2014). Maintenance of varietal diversity may reflect differences in traditional knowledge, heritage, and management (Pinton, 2003), as demonstrated by Amazonian

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on-farm diversity ranging from 1-8 cultivars per household (avg. 3.5) (Kawa et al., 2013), to 66 traditional varieties between five female farmers (Emperaire et al., 1997). Cassava's role as a traditional staple in the Amazon contrasts starkly with its relatively recent introduction as a cash crop in Southeast Asia and accompanying distribution of industrial varieties originating from local breeding programs. Near exclusive focus on productivity may lead to decreased diversity in increasingly commercial production schemes (Salick et al., 1997), a trend observed in many crops experiencing increased market integration (Tripp, 1994; Van Dusen and Taylor, 2005). However, maintenance of crop genetic resources also plays a role in the ability of farmers to adapt to environmental and market uncertainty (Almekinders and Louwaars, 2002, and references therein), which may suggest why Cambodian farmers reported higher varietal diversity than their Vietnamese counterparts in both the national and subnational surveys.

Varietal identity in our study was based on farmer perceptions, and not confirmed genetically. Cassava varietal identification is challenging for several reasons, including morphological differences resulting from genetic x environment interactions (Floro et al., 2018), and inconsistent naming including the use of nonstandard local names (Sardos et al., 2008; Rabbi et al., 2015), which may lead to high rates of misidentification (Floro et al., 2018). The mixing of several different stake sources by all traders interviewed likewise suggests that single fields planted with varietal mixes may be common, with unknown effects on exchange behavior.

Strengths and weaknesses of existing cassava seed systems

Shaw and Pautasso (2014) have highlighted the 'tension' between free movement of goods (usually considered beneficial; for example new varieties) and free movement of pathogens (detrimental) along the same pathways in plant disease pathosystems. In other words, highly efficient dissemination networks can translate to equally efficient in the spread of pests and disease (Shaw and Pautasso, 2014; Patil et al., 2015). Depending on the perspective of each actor, given properties of the seed system can often simultaneously be viewed positively or negatively. Informal networks efficiently disseminate the seeds of many crops, including cassava, in diverse contexts (Dyer et al., 2011; Fu et al., 2014; Coomes et al., 2015). Our findings provide a further example of an informal, yet effective, seed network serving a wide range of farmers, the existence of which had long been suggested by the widespread, spontaneous appearance of Thai and Vietnamese elite cassava varieties across Cambodia (Howeler & Ceballos, 2006).

Trade network structure plays a significant role in plant health epidemics (Moslonka-Lefebvre et al., 2011; Shaw and Pautasso, 2014; Hernandez Nopsa et al., 2015). Even in our single year sample, traders mediated exchanges over a scale of several hundred kilometers. Such networks have powerful reach for scaling uptake and dissemination of introduced germplasm, and potentially knowledge products and extension information, throughout the seed network – but only if actors who leverage trust and social capital are fully engaged. A core strength of informal seed systems, and simultaneous challenge to interventions in their functioning, is the deeply social character and abundance of trust-based interactions. The importance of personal acquaintances in the present study was complimented by the participation of strangers, especially unacquainted farmers and mobile stake traders. Traders' key roles in connectivity of the seed network may either be highly dependent on social relationships and trust (as in Tay Ninh), or purely opportunistic encounters (as in Ratanakiri). Traders therefore assume great importance in seed quality control. Recurrent, reciprocal relationships as described in Tay Ninh may serve as models for the development of acceptable quality declared seed supply to other areas. However the aforementioned practice of traders mixing stakes from different sources may both compromise varietal purity, and increase the potential distribution of infected materials.

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In addition to a nearly contiguous cassava production landscape, low crop diversification, low cassava varietal diversity, and frequent off-farm seed exchange increase vulnerability to the spread of pests and diseases. Cassava's lignified outer stem tissues do not exhibit obvious symptoms for a wide range of pathogens (Lozano et al., 1981), complicating diagnosis once stakes have been harvested from the mother plant, and thus separated from foliar and root symptoms.

Patterns of existing stake acquisition, especially purchase, observed in this study suggest the potential for demand-driven markets for quality seed, but these currently represent less than 0.1% of national stake supply in Cambodia and Vietnam. The absence of certification schemes or quality declared systems in both Vietnam and Cambodia mean there are currently no available sources for guaranteed clean material for the vast majority of farmers. In the absence of certification and phytosanitary screening mechanisms, farmers at the four subnational sites evaluated planting material quality based on traits associated with germination rather than pest or disease. Seed policies for regulating production and exchange of different seed classes do exist in both countries, and vegetatively propagated crops, including cassava, have recently been added to species lists. However regulations remain inconsistently applied to cassava's informal networks.

Key entry points for seed systems interventions

Conceptions of formal and informal seed systems are not antithetical, but rather possess complementary strengths and weaknesses with potential synergies (Almekinders and Louwaars, 2002). Seed systems are not binary, but span a complex range of elements combining into adapted, functional systems driven by the changing needs and demands of stakeholders. Interventions should therefore attempt to build systematically on the strengths of existing seed systems wherever possible to maximize impact. Several key interventions are suggested based on our results:

Improving farmer seed production and selection practices

The importance of farm-saved seed and farmer-to-farmer exchange in our study starkly contrasted with low levels of awareness of pest and disease, and action to improve seed quality. Education campaigns should promote improved seed production practices at the farm level to reduce seed degeneration rates and eliminate the re-use of contaminated stakes. Positive and negative selection have been shown to increase root yields under cassava mosaic disease pressure in susceptible cultivars (Mallowa et al., 2006). Because labor shortages and large field sizes often limit the practice of roguing or seed selection, the concept of the 'corner of prosperity' provides an important alternative. By partitioning an area of the farmer's field (10% is sufficient for own re-use) differential management may be applied for the production of high quality stems (Ceballos and Hershey, 2017).

Farmer-based associations, not mentioned by respondents in the current study, could become key actors in cassava stake production in Vietnam and Cambodia's largely decentralized exchange systems through schemes such as multiplication and sale of quality declared seed (QDS) (Legg et al., 2014).

Combining seed network analysis with surveillance and biophysical models

The structure and functioning of seed networks can provide context for distribution and incidence records of pathogens, helping to target sampling and mitigation efforts to the most effective actors and locations (Sutrave et al., 2012; Hernandez Nopsa et al., 2015; Buddenhagen et al., 2017; Andersen et al., 2018). Network analysis enables modeling of likely origins and anticipated movements of detected pathogens, while a more complete representation of the entire network can also provide predictions of potential multi-step paths through the system. Anticipating multiple steps

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can be important when cryptic symptoms and long latent periods complicate immediate detection of a pathogen, such that detection may imply that the pathogen has already spread further.

Cambodia's Northwestern provinces are a growing, highly connected cluster with distant incoming links, and should receive focused for monitoring and containment (Chadès et al., 2011). The high-intensity production areas of Southern Vietnam are home to a well-developed trader network through which infections risk rapidly spreading, and should similarly be a focus for preventative measures, dissemination of mitigation strategies, and eventually the release of resistant varieties.

By contrast, the relative isolation of Vietnam's Northern provinces is contemporaneous with low suitability for key pests including the cassava mealybug (*Phenacoccus manihoti*) (Yonow et al., 2017), and the insect vector of SLCMV, *Bemisia tabaci* whitefly (Campo et al., 2011). The combination of limited regional network connectivity, low potential for *B. tabaci*, and the current absence of the SLCMV virus suggest potential of the North's > 100,000 ha of cassava for low pathogen risk stake multiplication.

Integrating clean seed production schemes with informal seed networks

As phytosanitary pressures on cassava increase (Graziosi et al., 2016), formal 'clean seed' initiatives have already begun to emerge. Formal production pipelines are often linked to public breeding programs or specific projects, and monitor quality in terms of varietal purity, disease control, and physiological age. Fostering resilience in cassava seed systems will require cooperation with traders to bridge formal and informal systems (McGuire and Sperling, 2013), and to expand the reach of clean seed initiatives, extension, and disease monitoring. Links between the existing seed system and crop breeding networks which can supply sources of resistance will also prove important for long-term pathogen management (Garrett et al., 2017).

Considering industry's central role in root trade, increased involvement of private sector actors, including root processing factories and purchase points, could be impactful in promoting and scaling the use of quality seed. Organizations of cassava processors and industry members exist both in Thailand and Vietnam, and in the former are already involved in domestic seed multiplication. Their operational models should be further studied and lessons drawn from their experiences.

Seed regulations are often designed with commercial systems in mind (Spielman and Kennedy, 2016), and when applied to informal seed systems may discourage transparency. Engaging with informal seed networks from an exclusively punitive enforcement perspective would prove counterproductive (Wattnem, 2016). Institutional innovations such as seed clubs in Vietnam, have led to an officially recognized role of farmers in the seed system by the government through 'socialization in seed production and supply' in the rice sector (Tin et al., 2011). The potential impacts of adapting such approaches for vegetative crops should be studied.

Conclusions

Cassava seed systems in Vietnam and Cambodia were informal and self-regulated, with no active quality certification schemes. Traders played important roles in long-distance seed movement, yet in terms of predominant practice, transaction, and volumes, the use of farm-saved seed and exchanges among acquaintances within the community were most common. The notable exception was Tay Ninh, the highly commercialized 'cassava seed basket' of Southern Vietnam, which has developed an integrated farmer-trader system characterized by frequent (often annual) sale and replacement of seed, and a high degree of financially motivated exchanges. However full understanding of the trader network requires further study.

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The use of farmer saved seed is predominant in both countries, and at three out of four sites where we conducted in-depth inquiries. In both countries, 71 to 90% of seed used originated from within the commune, and 87 to 91% of provided planting materials also ended up replanted within the same commune. However, high-intensity production areas such as Tay Ninh and Battambang supply long-distance, trader-mediated exchange.

International imports of seed into Cambodia from neighboring countries accounted for 20% of seed acquisitions, with the trade of hundreds of thousands of stakes to 9 Cambodian provinces from Vietnam, to 4 provinces from Thailand, and to a single province from Laos. No outgoing exchanges from Cambodia were reported. Existing seed distribution networks originating in Thailand and Vietnam could be promising distribution hubs for the deployment of 'clean seed systems'.

Planned interventions in cassava seed systems should take into account the established roles of traders, root collection point owners, and other actors and their relationships with farmers, and explore opportunities to empower their current roles in the seed network for phytosanitary monitoring, seed system upscaling, and farmer education campaigns. Combining seed network analysis with biophysical, epidemiological, and further seed market evaluation can guide the design of effective interventions.

Policies and regulations for more formal cassava seed systems development do exist. However innovations should be sought to increase the volume of available quality seed in light of emerging seed-borne pests and diseases. Models from other crops and contexts could be adapted, such as the use of Quality Declared Seed (QDS), positive and negative selection, and seed clubs.

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Research ethics statement

The methods, data collection, and data handling protocols of this project were reviewed and approved by the International Center for Tropical Agriculture (CIAT) Institutional Review Board, and meet CIAT guidelines for research involving human subjects. Respondents provided oral informed consent prior to survey implementation, and all identifying data were anonymized in the resulting dataset. Participants in the national surveys, for whom plant tissue was also collected for SLCMV diagnostics, also provided written consent.

Data availability statement

The anonymized farmer survey data collected in this project is available on CIAT's dataverse portal at the following address: (temporary private link while manuscript is under review; permanent public link upon acceptance)

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Figures

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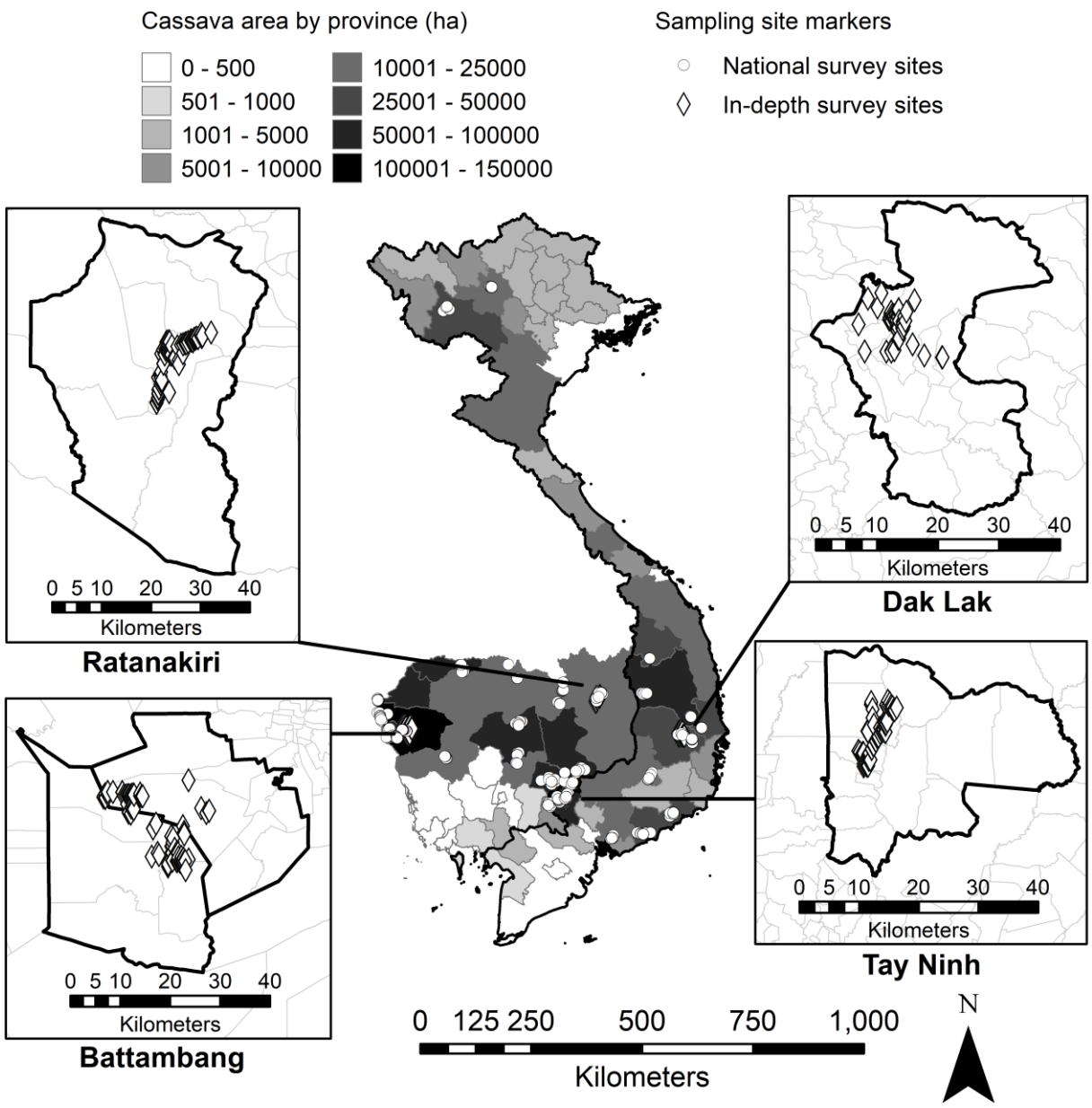

Figure 1. Project map indicating the location of farmer surveys in Vietnam and Cambodia in 2016-17. GPS locations of national and subnational survey sites are indicated by circle and diamond symbols, respectively. Thick borders in the inset maps indicate district boundaries. Greyscale shading indicates cassava area, calculated by province for 2016 (sources: General Statistics Office, Ministry of Planning and Investment, Vietnam; General Directorate of Agriculture, Ministry of Agriculture Forestry and Fisheries, Cambodia).

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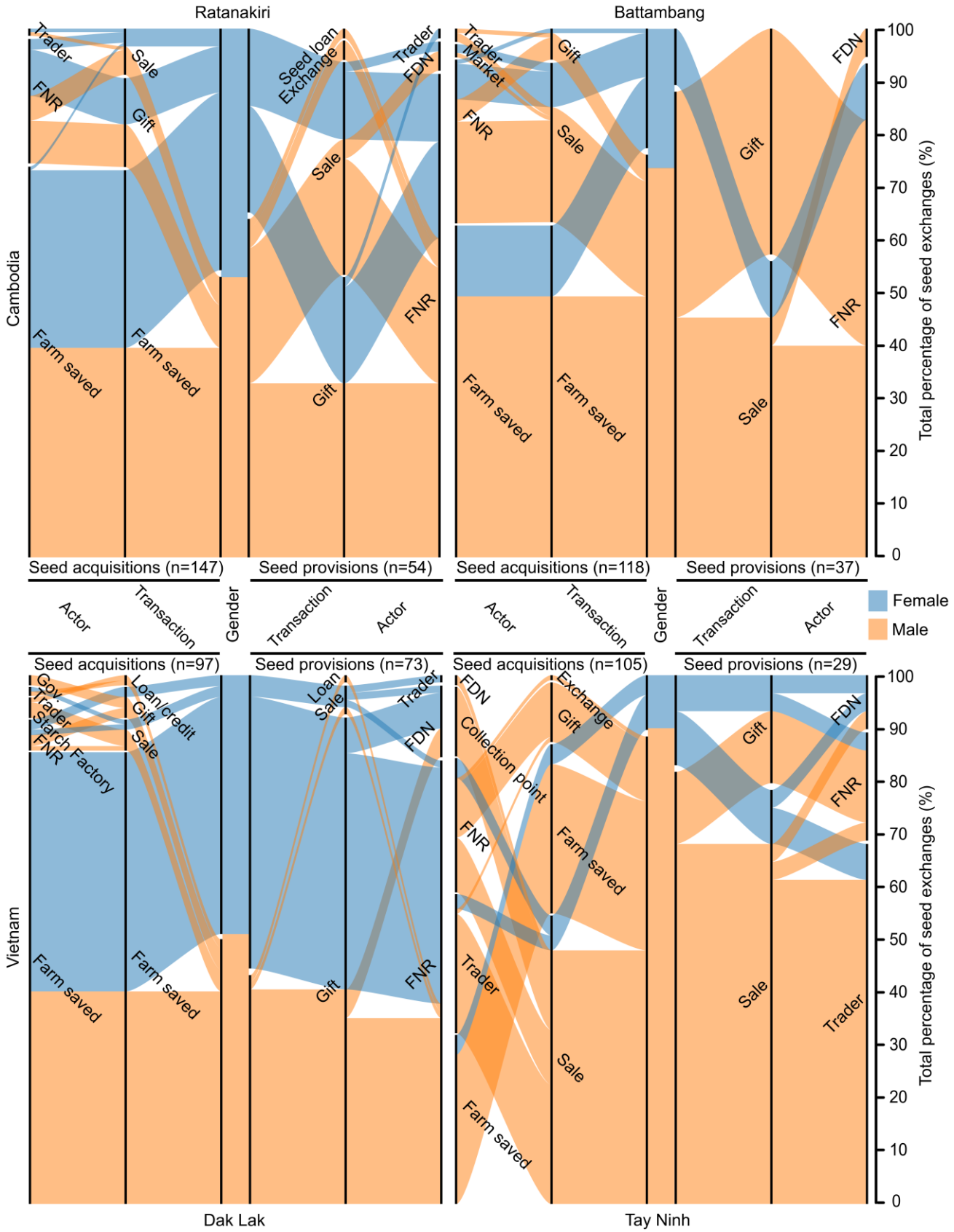

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Figure 2. Seed exchange acquisitions, provisions, actors, and mechanisms recorded in the 2016 growing season, at each of 4 sites in Cambodia and Vietnam, showing relationships between categories of actors and types of transactions. Low production intensity sites are located on the left, with high production intensity sites on the right. Total sample size is 100 for each site except Dak Lak (n=94). Black vertical bars represent 100% stacked percentages. 'Actor' indicates identified sources and sinks of cassava planting material, with 'FNR' indicating 'farmer/neighbor/relative', while 'FDN' indicates 'farmer I do not know personally'. 'Transaction' indicates socioeconomic mechanism of exchange for each acquisition and provision. Gender segments for each of acquisitions and provisions indicate the relative gendered contribution to the total number of transactions. The center columns of each subplot represent the gender proportion of survey respondents at each location.

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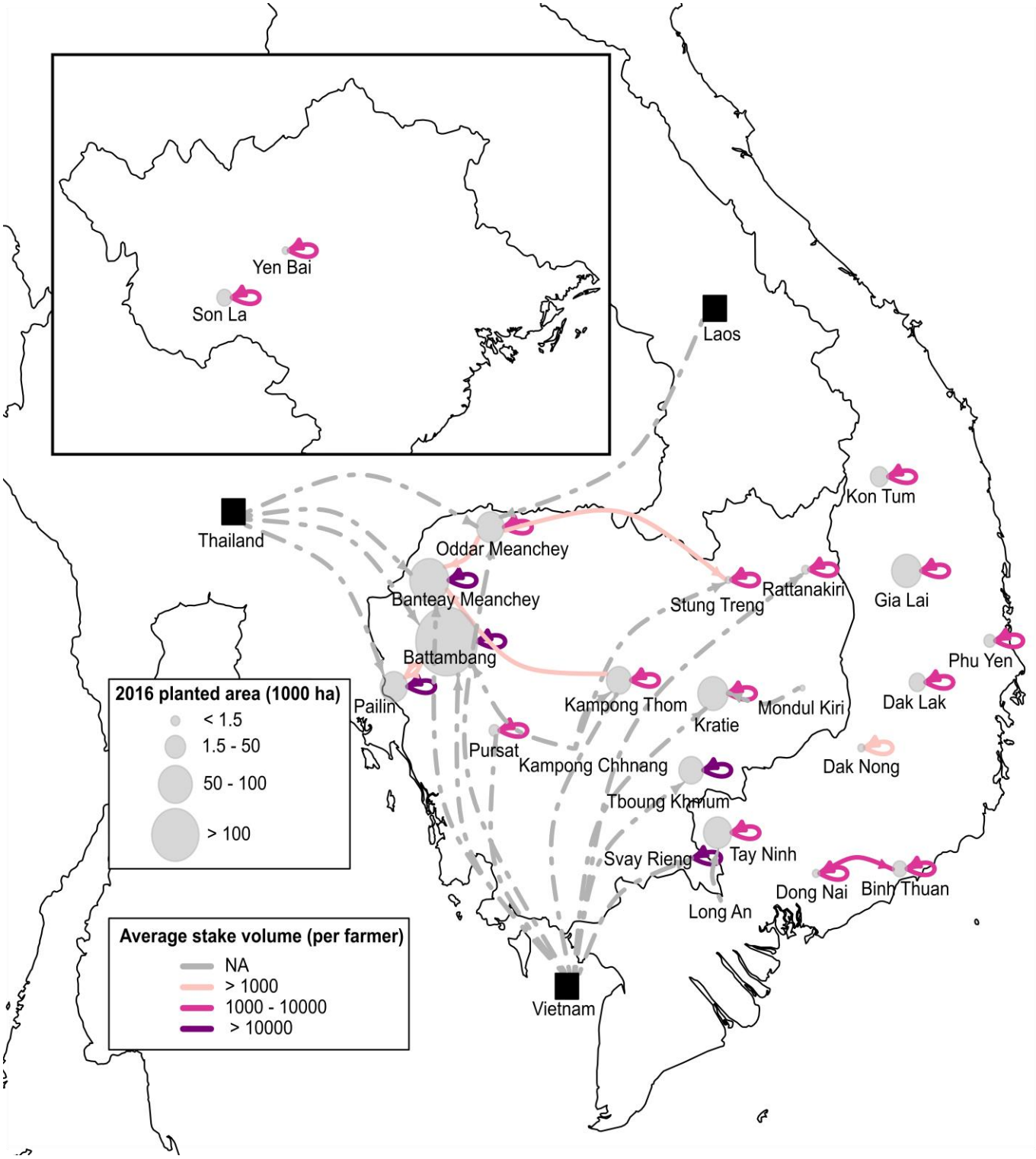

Figure 3a. Network graph representing stake exchange per surveyed farmer (links) between provinces (nodes) in 2016, aggregated from national-level survey of farmers (n=240) in 16 districts in Cambodia, and 15 districts in Vietnam (n=206). The inset map area represents Northern Vietnam. Self-loops indicate provisions that occurred within a given province. Link color represents volume of stakes exchanged, corrected by number of farmers surveyed (stakes exchange per farmer). Gray hashed links reflect instances of stake transactions from unsurveyed regions, where there was no

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formal sampling effort. Node size represents provincial cassava planted area in 2016 (ha). Black, square nodes represent stake movements where country, but not province name was provided by survey respondents. Note that the only stake movement data for Thailand and Laos were those mentioned by Cambodian and Vietnamese respondents. Links listed with 'unknown' destinations or origins are not illustrated. Because high production districts within provinces were targeted for this survey, volumes of seed exchange should be considered the upper-end of the likely province-wide average stake exchanges per farmer.

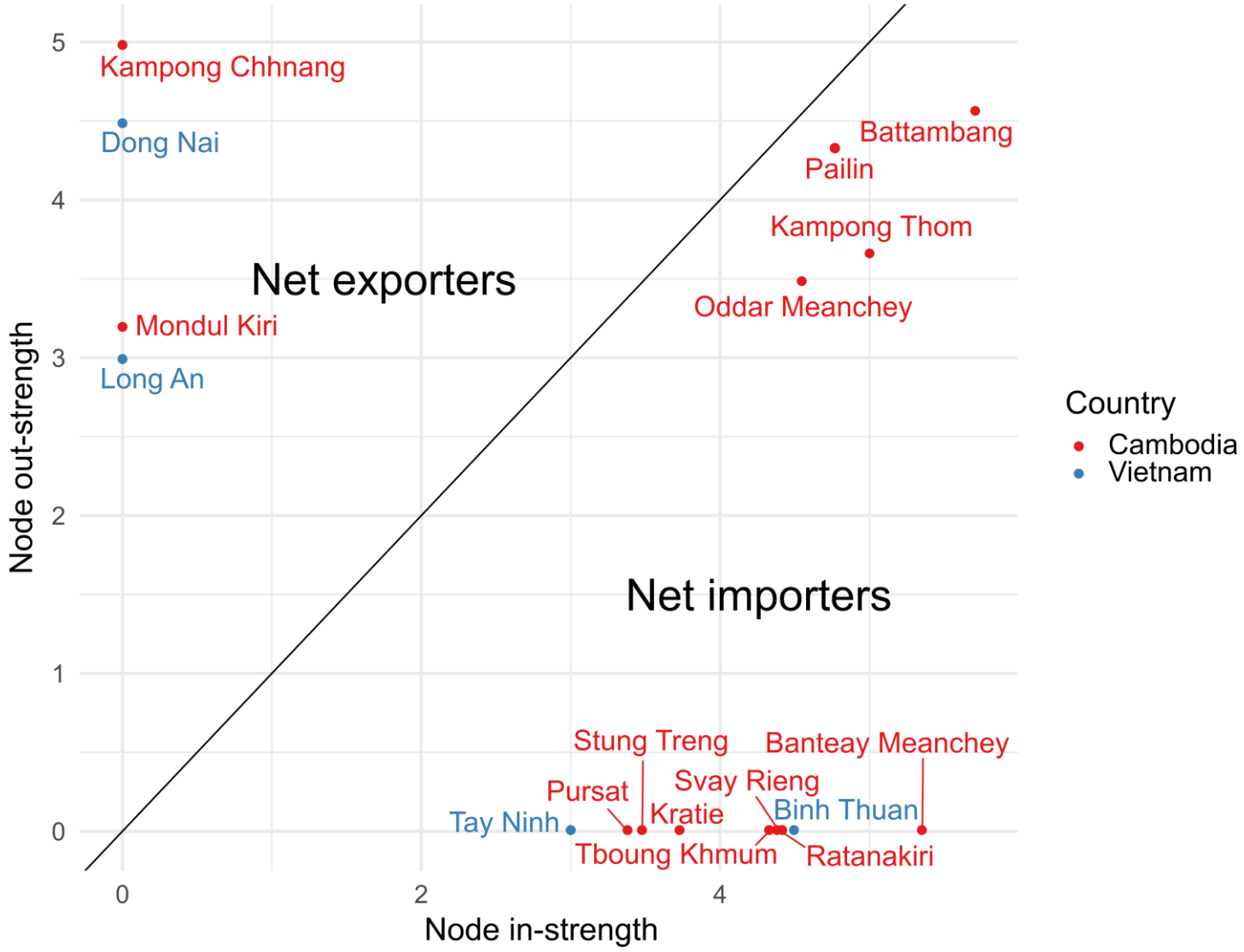

Figure 3b. Log10-transformed node strength, the weight of links (in this case, number of stakes per farmer), by province. In-strength is the number of incoming stakes, out-strength is the number of outgoing stakes. Provinces above the bisectrix can be considered net-exporters, while provinces below the bisectrix represent net-importers.

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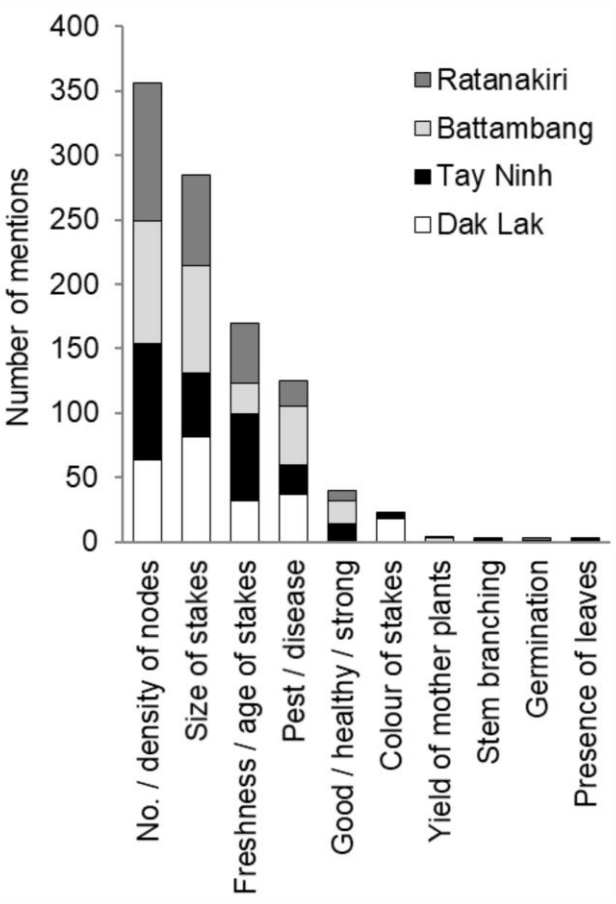

Figure 4. Number of mentions of quality indicators considered during selection of cassava planting material by survey respondents at 4 subnational sampling sites in Vietnam and Cambodia. Responses were free-listed, and thus multiple responses were allowed per respondent. Free-listed responses were categorized into dominant themes post survey.

Tables

Table 1. Number of varieties maintained at the farm level by producers in the 2016-17 cassava season in both national and subnational surveys (% respondents), with VN indicating Vietnam and KH indicating Cambodia.

	National surveys		Subnational surveys			
			High intensity		Low intensity	
Number of varieties	KH	VN	Battambang (KH)	Tay Ninh (VN)	Ratanakiri (KH)	Dak Lak (VN)
1	69	93	74	99	54	97
2	25	6	24	1	41	2
3	6	1	1	0	3	1
4	0	0	1	0	2	0
Sample (n)	240	206	100	100	100	94
Average # varieties (SD)	1.38 (0.62)	1.09 (0.30)	1.29 (0.54)	1.01 (0.1)	1.53 (0.66)	1.04 (0.25)
Range	1-4	1-3	1-4	1-2	1-4	1-3

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Table 2. Frequency of cassava seed purchase and average total expenditure on seed per household (expressed in USD adjusted to 2017 exchange rate) when cassava seed was purchased in three consecutive seasons at high and low production intensity sites in Cambodia (KH) and Vietnam (VN).

	High intensity				Low intensity			
	Battambang (KH)		Tay Ninh (VN)		Ratanakiri (KH)		Dak Lak (VN)	
	% buying	avg. USD	% buying	avg. USD	% buying	avg. USD	% buying	avg. USD
2014	22	342	33	132	16	83	10	84
2015	29	285	52	199	19	248	10	70
2016	30	243	63	228	14	82	7	54

Table 3. Seed source and acquisition types reported in Cambodia (KH) and Vietnam (VN) in 2016, presented as percentages of total recorded seed exchanges. 'Ac.' denotes seed acquisition, while 'P.' denotes seed provision.

	National surveys				Subnational surveys							
					High intensity				Low intensity			
	KH		VN		Battambang (KH)		Tay Ninh (VN)		Ratanakiri (KH)		Dak Lak (VN)	
Source	Ac.	P.	Ac.	P.	Ac.	P.	Ac.	P.	Ac.	P.	Ac.	P.
Own stock	47		64		64		32		74		86	
Acquaintance (within community)	26	82	20	78	27	95	24	21	22	91	6	82
Acquaintance (outside community)	4	0	4	1	4	0	2	0	2	2	0	3
Other farmer (non-acquaintance)	3	18	1	13	0	5	2	10	0	6	0	14
Local market	1	0	0	0	3	0	0	0	1	0	0	0
Agroinput dealer	0	0	6	0	0	0	0	0	0	0	0	0
Starch factory	1	0	0	0	0	0	0	0	0	0	4	0
Community collection point	0	0	0	0	0	0	13	0	0	0	0	0
Trader	18	0	3	9	3	0	27	69	1	2	2	1
Municipality / district office	0	0	1	0	0	0	0	0	0	0	1	0
Government research organization	0	0	0	0	0	0	0	0	0	0	1	0
Total N transactions	381	130	234	104	118	37	105	29	147	54	97	73
Sample N (individuals)	240		206		100		100		100		94	

Table 4. Methods of seed exchange reported at one high and one low cassava production intensity site each in Cambodia (KH) and Vietnam (VN) in 2016, presented as percentages of total exchanges at each site. 'Ac.' denotes seed acquisition, while 'P.' denotes seed provision.

	National surveys				Subnational surveys							
					High intensity				Low intensity			
	KH		VN		Battambang (KH)		Tay Ninh (VN)		Ratanakiri (KH)		Dak Lak (VN)	
Method of exchange	Ac.	P.	Ac.	P.	Ac.	P.	Ac.	P.	Ac.	P.	Ac.	P.
Save own stocks	47		65		64		32		74		86	
Exchange/barter	0	2	7	45	0	0	1	0	0	4	0	0
Gift	10	62	13	34	6	43	11	21	17	54	6	93
Purchase	43	36	15	21	31	57	55	79	9	41	6	5
Voucher/coupon	0	1	0	0	0	0	0	0	0	0	0	0
Seed Loan	0	0	0	0	0	0	0	0	0	2	1	0
Money credit	0	0	0	0	0	0	0	0	0	0	1	1
Total N transactions	381	130	234	104	118	37	105	29	147	54	97	73

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Table 5. Geography of stake exchange in the 2016 field season from both national and subnational surveys, displayed in percentages of overall stake transactions recorded at each site. 'Ac.' denotes seed acquisition, while 'P.' denotes seed provision. Self-provisioning from the previous year is considered as one transaction.

	National surveys				Subnational surveys							
					High intensity				Low intensity			
	KH		VN		Battambang (KH)		Tay Ninh (VN)		Ratanakiri (KH)		Dak Lak (VN)	
Source	Ac.	P.	Ac.	P.	Ac.	P.	Ac.	P.	Ac.	P.	Ac.	P.
Own field	47		64		64		30		70		86	
Same commune	24	91	26	87	23	73	65	62	25	91	0	95
Other commune – same district	4	2	2	0	3	8	3	10	1	2	0	1
Other district – same province	2	4	3	2	5	8	0	0	1	0	0	0
Other province – same country	2	3	5	0	4	8	0	0	2	2	7	0
Other country	20	0	0	0	1	0	0	0	0	0	0	0
Unknown	1	1	1	12	1	3	2	28	1	6	7	4
Total n transactions	381	130	234	104	118	37	105	29	147	54	97	73
Sample n (individuals)	240		206		100		100		100		94	

Table 6. Summary of seed policy frameworks of Vietnam and Cambodia (2017).

Country	Vietnam	Cambodia
Key authorities	• National level: Ministry of Agriculture and Rural Development (MARD) • Provincial level: Department of Agricultural and Rural Development (DARD) • District level: Sub-MARD • Department of Crop Production (DCP): quality control of commercial seed (public and private) • National Centre for Variety Evaluation and Seed Certification (NCVESC): organizes testing of new varieties and conducts seed quality certification of crop seeds • Department of Plant Protection (PPD): managing pests and diseases of crops, monitoring health of imported seeds, pathology • New varieties issued from: MARD, the Ministry of Education and Training (MET), and private seed companies	• National level: Ministry of Agriculture, Forestry and Fisheries (MAFF) and General directorate of agriculture (GDA) • The Cambodian Agricultural Research and Development Institute (CARDI) • Seed law implementation, including development of related articles – MAFF/GDA • MAFF is responsible for seed testing • Ownership rights of new seeds are certified by MIME after all technical tests are completed and officially approved by MAFF • Registration of seed companies is done by the Ministry of Commerce • Registration of seed associations is done by the Ministry of Interior • Registration of community seed based organizations is done by MAFF
Key legislation	• Ordinance on Plant Varieties (2004) • Law on intellectual property (50/2005/QH11) • Amendment of Intellectual Property Law (2009) • Decree No. 07/CP (1996) • Decree No. 88/2010/ND-CP • Decree No. 187/2013/ND-CP • MARD decision-35/2008; to legalize and stimulate farmer individuals, groups, clubs, and cooperatives who and which can do breeding, selection, seed production for household use and seed exchange and supply in the market • Joined UPOV (1991) in 2006 • MARD circular 11/2013/TT-BNNPTNT; applies legislation governing breeders' rights to	• Law on seed management and plant breeder's rights (2008). • Sub-decree 69; identified as Legal Framework for Agricultural Materials and Products • Sub-decree 15 on phytosanitary inspection • Sub-decree 118 assigned responsibilities for seed management to the GDA under the MAFF • Working with UPOV for development of seed laws, but not yet a signatory of the convention

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	21 vegetatively propagated crops (no. 16 *Manihot esculenta* Crantz)	
Seed certification classes	• *Breeder seed (author's seed):* the author(s) has/have selected, crossbred or taken from the gene fund with stable heredity • *Foundation seed:* produced from breeder seed with strict processes for production, and quality standards stipulated by the State • *Certified seed (commercial seed):* one of the last generations of foundation seed, used for large-scale production but not kept as seed • *Local seed:* existed in a locality for a long time in a stable manner, with heritable properties, and distinctive features	• *Breeder seed:* produced by plant breeders using NS in a single progeny selection approach • *Foundation seed:* the most closely controlled class, grown from seed supplied by the breeder or owner of the variety • *Registered* seed: grown from foundation seed; is a multiplication class of seed with standards less strict than foundation class • *Certified seed (commercial seed):* progeny of registered seed, using standards less stringent than registered seed

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