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RESEARCH ARTICLE

A proposed framework for accelerating technology trajectories in agriculture: a case study in China

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Abstract Precision agriculture (PA) technologies have great potential for promoting sustainable intensification of food production, ensuring targeted delivery of agricultural inputs, and hence food security and environmental protection. The benefits of PA technologies are applicable across a broad range of agronomic, environmental and rural socio-economic contexts globally. However, farmer and land-manager adoption in low to middle income countries has typically been slower than that observed in more affluent countries. China is currently engaged in the process of agricultural modernisation to ensure food security for its 1.4 billion population and has developed a portfolio of policies designed to improve food security, while simultaneously promoting environmental protection. Particular attention has been paid to the reduction of agricultural inputs such as fertilisers and pesticides. The widespread adoption of PA technologies across the Chinese agricultural landscape is central to the success of these policies. However, socio-economic and cultural barriers, farm scale, (in particular the prevalence of smaller family farms) and demographic changes in the rural population, (for example, the movement of younger people to the cities) represent barriers to PA adoption across China. A framework for ensuring an acceptable and accelerated PA technology trajectory is proposed which combines systematic understanding of farmer and end-user priorities and preferences for technology design throughout the technology development process, and subsequent end-user requirements for implementation (including demonstration of economic and agronomic benefits, and knowledge transfer). Future research will validate the framework against qualitative and quantitative socio-economic, cultural and agronomic indicators of successful, or otherwise, PA implementation. The results will provide the evidence upon which to develop further policies regarding how to secure sustainable food production and how best to implement PA in China, as well as practical recommendations for optimising end-user uptake.

Keywords precision agriculture, farmer adoption, technological innovation

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1 Introduction

Precision Agriculture (PA) technology is promoted as one means of ensuring sustainable intensification across all aspects of agricultural production[1]. In crop production, PA relates to a suite of ‘Site-Specific Crop Management’ technologies that are specifically designed to produce more with less inputs and environmental impacts, based on observing, measuring and responding to inter- and intra-field variability in production. Wentworth[2], suggests that various motivational factors may influence farmer and land–manager adoption[3,4]. Despite the recognized benefits of PA in terms of improved yields, farm profitability, and positive environmental impacts, on-farm adoption rates have been demonstrated to vary across different countries and regions. Developing countries in particular may lag behind developed countries in their rate of farmer adoption of PA technologies, despite the potential of these technologies to mitigate pressing social and agricultural challenges in less affluent countries[5]. A case in point, as

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well as food insecurity linked to climatic and agronomic factors, are the additional problems associated with rural depopulation and reduced labor resources[6]. One such country is China, where there is evidence that the uptake of agri-technologies among Chinese farmers falls significantly behind the US, Europe, South America and Australasia[7,8]. China has undergone significant economic development in recent decades[9], and its agricultural sector is in the process of modernisation to ensure food security for its 1.39 billion population. At the same time, changing consumer preferences, dwindling natural resources, environmental degradation, rapid urbanisation, and the fragmentation of the agricultural landscape (which is dominated by small-scale farms), and climatic uncertainties further complicate production priorities and food security (see *inter alia*[10–12]). Ubiquitous adoption of PA technologies across China has been identified within agricultural policy as one of the major tasks of the Chinese 13th Five-Year Plan1) for economic growth. This prioritises the need to accelerate the adoption of precision farming technologies, together with the need for the adoption of information gathering systems, accessible management of digital information, intelligent decision-making systems, and precision management (e.g., water-fertilizer-pesticide) implementation systems nationwide[13]. Despite government policies being enacted to promote sustainable intensification in agriculture, and the potential of these technologies to address some of the distinct agri-social challenges faced in China, the adoption of PA is not widespread and is currently concentrated on large-scale commercial agricultural production operations located in northern China. The use of PA technologies has not filtered down to smaller family farms, where adoption rates are low[14].

While innovations in PA technology continue to develop, with new PA techniques emerging rapidly, the wide-ranging benefits of PA can only be realized across all farm scales in China if an innovation trajectory is developed and implemented that considers local preferences and priorities for technological innovations *and* matches national policies to end-user needs. At the same time, food security may depend on implementing *de minimis* standards (e.g., in relation to food safety or the environmental impacts of agriculture). These must be integrated into an approach which respects both traditional measures of agronomic success (e.g., improved yields, economic benefits), national and international policies linked to food security and environmental conservation or remediation, and the socio-economic and cultural welfare of evolving rural populations. Thus, the assessment of the effectiveness of any agronomic technological innovation will need to accommodate multiple variables, and integrate these into a common assessment framework.

This paper therefore seeks to provide a framework for PA development and adoption, relevant to the Chinese socio-economic, agronomic and cultural context, to ensure equitable access to PA technologies across all farm scales and farming structures (i.e., cooperatives). The framework was developed in the context of a PA project ("PAFIC" , Precision Agriculture for Family Farms in China2)) aimed at crop production, but it could equally be applied to animal systems and other agricultural contexts. Guided by the principles of Responsible Research and Innovation (RRI), integrated with diffusion of innovation methodologies, the aim is to foster the design of inclusive and sustainable research and innovation[15] by promoting the involvement of a broad range of stakeholders throughout the (co)-innovation process. To populate and achieve this goal, a conceptual framework to support equitable PA development and adoption across different Chinese agronomic conditions, crop types and farm scales is proposed. This will enable "outcomes" from the innovation process to align with national and local priorities, accelerate the development and implementation trajectory of PA technologies, and promote national food security, while simultaneously preventing unwanted negative outcomes, such as the marginalisation of rural communities from emerging (agricultural) technologies, rural poverty and continued rural depopulation.

As technological innovations, including PA, should be designed to address the needs of society, there is a need to understand the Chinese socio-cultural and political context in which PA technologies will be developed and implemented in order to guide technology development and implementation. This paper will therefore provide a concise introduction to precision agriculture technologies before considering the political context shaping the adoption of PA in China and presenting the proposed implementation framework.

2 Precision agriculture technology

2.1 Background

The role of PA technologies in tackling global issues of food security and environmental protection has been well documented[16,17]. PA technologies have been under development since the 1980s and are broadly defined as "*farming techniques [that] support farmers to select and apply the right inputs at the right time and at the right scale*"[1]. A number of different types of PA technology

1) [1] China's Five Year Plans represent the countries social and economic development initiatives. China is currently in the 13th five year planning period that covers 2016–2020

2) [2] Precision Agriculture for Family Farms in China "PAFIC" is joint funded by the funded by the UK-China Research and Innovation Partnership Fund (Newton Programme)

exist including; disease diagnostics[18,19]; soil and yield mapping using a global navigation satellite system (GNSS), GNSS tractor guidance systems, variable-rate input application[20], precision nutrition and health and welfare monitoring for animals[21], and remote sensing[22]. PA potentially delivers three fundamental benefits to farmers; these are; first, economic benefits through reductions in farm expenditure via the controlled application of agricultural inputs[23]; second, increased production levels due to targeted management of in-field (or intra-animal) variability[24] and; third, environmental benefits through the precise application of agro-chemical applications (such as fertilisers, pesticides or antimicrobials), which will increase compliance with national environmental legislation[12].

Within the scientific community the benefits of PA for improving farm productivity, profitability and reduced environmental impacts of farming practices are increasingly being realized, and further technological advances are continually being developed[25]. However, there is a recognized disconnect between technology development and end-user uptake, and the challenge of how to translate scientific research into usable on-farm solutions, support farmer acceptance and adoption, and facilitate long-term adoption and implementation remains problematic.

2.2 Factors influencing adoption

An important potential driver of PA adoption is that lower-cost technologies become more accessible to smaller farms. At present, it is recognized that larger farms have greater access to technological innovation because of affordability in relation to start-up costs[20]. Several studies have attempted to explore the factors influencing the uptake of PA innovations, and consider the barriers to adoption faced by farmers (Table 1).

The significant economic and skills investments required, and the difficulty in evaluating agronomic returns due to variations in input prices and market volatilities are widely acknowledged to impede technology uptake and adoption[8,26–28]. Factors including farmer and farm characteristics, such as attitudes toward risks and risk taking, computer literacy and farm size are also considered significant influencers of PA adoption[14,25]. These factors potentially impede or could limit the adoption, of PA technologies by Chinese farmers.

While the economic and environmental benefits of PA have been demonstrated in China (*inter alia*[33]) and there is a substantive body of research focused on further refining PA technologies and their applications, to the best of the authors' knowledge, there has been limited investigation in China that has explored farmer and end-user attitudes and perceptions toward PA technologies[14]. It is likely that many of the factors influencing adoption have cross-cultural validity. However, this cannot be assumed. In China, the prominence of small scale family-run farms associated with different levels of mechanisation, production scale and farmer education[14,33], and variations in the scientific research and policy context, may generate a range of context-specific factors that impact upon innovation adoption trajectories.

3 Precision agriculture adoption in china: a case study

3.1 The context of Chinese agriculture and food security requirements

China is an important country within the global food web, producing one quarter of the world's grain and feeding one fifth of the world's population on only ten percent of the world's arable land[34]. Agricultural production is subject to an interplay of pressures, including demographic changes from sustained population growth, rural-urban migration and changing consumer preferences. These factors are combined with pressures on natural resources (including land and water) that have been negatively impacted by the inefficient use of, and over reliance upon, agricultural fertilisers to maintain yields (with use increasing 4% annually, amounting to one third of global fertilizer usage)[33]. China's response to its social and environmental challenges is affected by its social and agricultural landscape, which is characterized by a preponderance of small scale 'family farms' that account for 99.2% of all farms in China (Table 2), which are relatively inefficient in terms of food production[35]. These factors combine to threaten national food security, and pose a challenge to adoption of potential solutions[10–12,36].

Significant reforms to Chinese agricultural policies have occurred in the last two decades, with food security (or 'grain security' as it is referred to nationally), together with the need to reduce rural poverty, motivating change[37]. Underpinning these agricultural reforms have been policies that support a shift away from small-plot subsistence farming structures, which are favored by the household responsibility system (HRS), toward small to medium-sized commercial family farms, and the promotion of larger farms through the amalgamation of small family farms into larger farm cooperatives, or state run corporate farms. Although policies focused on these issues have slowly gathered momentum, this has led to a current considerable variation in farm sizes and structures and, arguably, increased national diversity in levels of technology adoption readiness (Table 2).

Farm restructuring has been underpinned by changes in regulations relating to land ownership and transferability of rights to production. The reforms are in response to the view that the preponderance of small farms has led to lower efficiency, and that larger enterprises could more

Table 1 Factors influencing the adoption of precision farming technologies

Factors influencing adoption	Overview	References
Cost (i.e., financial investments)	Capital costs associated with PA technologies can be high, particularly in times of low commodity prices. The high costs of these technologies may disproportionately favor larger farms that have the capital to invest in the associated technologies. In addition to the costs of the technology, there are additional costs of extension services required to interpret data and formulate management plans. Moreover, while the costs are clear, it is difficult for farmers to identify the financial benefits of PA technology	[26] [8] [27] [28]
Level of mechanisation within a farming system	Many technologies are aimed at mechanised operation and are not suitable for manual operations. E.g., Yield mapping in processing tomatoes using a mechanised harvest system is possible. However, mechanisation is not possible when farming market tomatoes	[27]
Skills	The adoption of PA technologies requires farmers to invest in learning a new skill, using information systems and interpreting data outputs which can require significant time investments. PA technologies may be perceived to be complex and difficult to use. Moreover, agricultural workers may give low prioritisation to the analysis of data over more practical tasks (i.e., harvesting). It is also recognized that the identification of in-field management zones requires longitudinal data collection and staff retention or at least acquisition of new staff with appropriate skills. Trained and skilled agricultural workers may also be difficult to find in rural areas	[8] [29] [30] [31] [27]
Socio-demographics	Farm size influences adoption, with larger farms being more likely to adopt PA technologies owing to increased levels of awareness. Access to information and ability to invest may also be more problematic on smaller farms, where farmers may be less well informed about PA and are less likely to be adopters Farmer education level influences adoption; farmers educated to degree level are more likely to adopt PA technologies, training in which has become part of agricultural education at universities Younger farmers are potentially more highly educated and more willing to innovate; older farmers may be more reluctant to engage owing to the reduced likelihood of paying off investments in technology and lowered time periods over which they can witness accrual of benefits	[29] [30] [27] [8] [27] [29]
Technology compatibility	Incompatibility of software and hardware from different PA manufacturers may present a barrier to adoption	[30] [27]
Perceived benefit	The primary benefits of PA may be difficult for the farmer to quantify	[30] [27]
Perceived risk	There may be a perceived risk within rural communities for negative impacts in relation to traditional cultures, and socio-demographic composition New technological innovations are likely to be perceived as being riskier than traditional practices	[26] [29]
Data security	Due to potential interpretation complexity and time commitments linked to PA, analysis of data collected on farm is often outsourced to consultants or contractors. Outsourcing of farm data carries concerns relating to data insecurity, and fears of misuse	[30] [27]
Advisory service (farmer support)	Better advisory services, more information and better training opportunities are required to support the adoption of PA technologies particularly during the introductory stages of adoption, and to aid with the interpretation of data Farm advisory specialists and agronomy advisors may represent a limited resource in terms of availability and/or lack knowledge and training in specialist approaches to PA, and are therefore unable to provide adequate support to farmers regarding technology adoption There is currently a lack of industry wide protocols for the application PA techniques	[27] [8] [27] [31]
Farming subsidies	High levels of farming subsidies can reduce incentives to farmers to manage farms based on maximum profitability, and eliminate farmer motivation to consider economising technologies such as PA	[27]
Farm demonstrations	There has been a decline in the number of farm demonstrations of PA which provide information to farmers and support proficiency in the use of technology	[32]

successfully apply modern agricultural methods over a greater area in order to secure food sovereignty, and promote economic growth in agricultural production[38]. The promotion of technological advances in agricultural practice in China is occurring concurrently and is in part, reliant upon structural changes to the national agricultural land ownership via policy to promote the consolidation of family farms into larger enterprises.

3.2 China's land ownership and transfer policy and policy initiatives for agricultural modernisation

While the reforms to land ownership, tenure and transfer rights have been fundamental in the modernisation of Chinese agriculture, levels of uptake of PA technologies have potentially been negatively influenced by the very policies intended to promote their adoption. Historic land

Table 2 Characterization of Chinese farms at different scales

Scale	Description	Number (households)	Percentage of farms in China	Average size/ha
Small farms	Very small operations for personal food production	266.07million	99.2%	0.41
Farm cooperatives	Collaborations between groups of family famers to increase scale to improve commercial output and economic functioning	1.39 million	0.52%	
Family farms	Farms at commercial scale (typically) managed and predominantly operated by a single family	0.88 million	0.33%	13.38
Large government/State managed farms	Typically state run farms where it is easy to adopt PA in line with emerging Chinese policy	1789	0.0007%	3466.67

Note: Adapted from China Statistical Yearbook and data released by authorities.

use and transfer policies have influenced agricultural production in China, not least because the household responsibility system was responsible for the fragmentation of the Chinese agricultural landscape. Previously, short tenures and the threat of reallocation of land by village officials resulted in instability, rural poverty, high rates of rural-urban migration and limited investment in the land and production methods[38,39]. In 1984, farmers' rights to own collectively their land, but operate individually, was extended to 15- years (from an initial 2-3-year base), and subsequently land rights have been further extended to 30-years during the 1990s. This provided farmers with greater levels of security, and an improved scope for investment and prosperity through farming[37]. However, despite greater security of land leases, Chinese farmers possessed no land transfer rights, and there was no formalised market for land transfer until legislation was introduced in 2002 and 2007. For the first time, these laws enabled farmers to use, profit from and transfer the land during their lease periods. Land transfer markets are important for increasing the value of farm lands, promoting land markets and the agri-business sector. It is proposed that land transfer will also facilitate the application of modern agricultural techniques, such as PA. All of these are central to achieving Chinese agricultural policy objectives, but may not ultimately deliver in line with government policy. By the end of 2016, the land transfer area had reached over 30.7 million ha (460 million mu), accounting for more than a third of the total land area, although the level, speed and motivation of farmers to transfer land has been subject to considerable variation. Despite evidence of significant land transfer in China, the process is still in its infancy, with small farms continuing to be a dominant feature of the agricultural landscape. The speed of land transfer is impacted by a lack of a universal or formalised land registration system established for this purpose, together with low levels of awareness of land transfer rights among famers[37,39]. Where land has been transferred, farmers are faced with farming increased land areas to which they have no historical connection, or may be farming fragmented and discontinuous plots, rather than continuous land areas. Land fragmentation across farms may be particularly problematic for PA adoption.

While land transfer has begun to change the structure of Chinese farms, at present changes have been insufficient in scale and outcome. Currently there is a co-existence of polarized situations, with a small number of farms operating at a large-scale (typically government run commercial farms located predominantly in the North of the country) (Table 2; *inter alia*[37,39]), or larger fragmented farms. At present, family farms lack both the capital and incentive to invest in agricultural technologies, including PA. In common with other parts of the world, China faces problems associated with declining rural populations and rural-urban drift[40,41], which disproportionately involves younger people moving to cities, and also disproportionately involves men, leaving older women to manage farms[42]. Thus, rural populations are characterized as aging, with little experience of digital technologies[43,44], including those applied to agriculture.

Despite policy incentives that encourage the amalgamation of small farms to promote agricultural modernisation, it must be recognized that not all farmers will want to transfer land to be managed as part of larger enterprises. There is also value in preserving rural ways of life, and specific cultural issues associated with living and working in the countryside[45,46]. As a consequence, it is inevitable that, despite the importance of policies to promote agricultural modernisation, the cultural tradition of small-scale farming in China may remain a part of the country's agricultural landscape. Thus, it is arguable that the policy focus driving the modernisation of Chinese agriculture through the promotion of a large scale commercial agriculture sector, in line with the country's industrial growth goals, could give way to ethical concerns regarding the marginalisation of traditional, small-scale agriculture and deepen divides both within and between rural and urban communities, without achieving significant improvements from larger scale farming and the adoption of PA. This policy tension also highlights the risk that China could lag further behind global leaders in modern agricultural technology adoption[38]. To better achieve

Chinese policy goals, and avoid the lag between PA development and adoption, it is important to consider the needs, priorities and views of end-users. Such an outcome can be facilitated by a more inclusive framework for the development and adoption of PA that takes account of, and responds to, stakeholder priorities and preferences along the entirety of the innovation pathway.

In addition to policies aimed at reforming the agricultural landscape in China, and in line with global sustainable development targets, China's agri-food policy also accentuates the need to ensure food security by increasing productivity while at the same time reducing environmental impacts caused by the over application of agricultural inputs. Chinese agri-food policy has recognized the need to strengthen internal food security strategies, and, as the focus of the 13th five-year plan illustrates, the country has embraced the concept of sustainable intensification and technological innovation applied to agriculture[47]. PA technologies are viewed as an integral part of the solution to address China's food security challenges, a means of addressing sustainable agriculture objectives and contributing to the modernisation of Chinese agriculture[48]. The transfer of land is fundamental to ensure food security and to promote adoption of precision technologies. In addition to this, the Chinese government and the Ministry of Agriculture (MoA) has supported a suite of activities that support the nation's agricultural modernisation goals and in so doing, provide an environment conducive to the widespread adoption of PA technologies. Examples include the designation of 20-one national modern agriculture demonstration areas since 2012, to showcase the transition from traditional small scale farming practices to 'modern agriculture' including the demonstration of advanced precision farming technologies and supporting the growth of farming cooperatives and professional operating systems, so as to increase the intensification of farming, production and subsequently improve farmer incomes[49].

Farmer co-operatives have been widely promoted in order to increase the number of cooperatives nationally and the number of farmers as members, the quality of produce and the efficiency of farm land. Standardised development of cooperatives has been supported through strengthening support policies including the implementation of agricultural projects which increase cooperative income to support growth, and provide educational training opportunities and improved access to markets[50]. For example, in 2014, the Chinese MoA launched initiatives to strengthen the provision of agronomic information into villages and farming households. Pilot projects in 10 provinces were established to create 'information stations' within villages. The stations play an important role in accelerating the modernisation of agriculture by allowing farmers to obtain advice in relation to policy, technology, market behavior, in addition to agronomic information and support. The initiative has also promoted the expansion of telecommunications supporting the use of e-commerce in rural areas, narrowing the rural-urban divide and transforming farmer's access to market distribution channels, by for example, allowing them to sell directly via online platforms[51].

The development of technology services and new farm operation models have aimed to further encourage the adoption of modern farm management practices and support the adoption of advanced agricultural technologies on family farms[52]. For example, the delegated services provided by agricultural contractors and consultancies are promoted to encourage ordinary farmers to take part in advanced agricultural practices. In so doing, farmers and other farm operators can entrust agricultural service organizations to complete whole or partial agricultural production tasks including, ploughing, planting, and harvesting without transferring land or management rights[53]. The approach assumes that engagement with agricultural service organizations and companies will allow farmers to benefit from modern farm management practices and agricultural technologies by drawing on the knowledge and skills of trained professionals and operators, thus helping to overcome the difficulties associated with the adoption of new technologies, their technical operation and interpretation of results. Further government initiatives to support the modernisation of agriculture include the state provision of agricultural insurance premium subsidies to stabilize farmers' incomes, and in so doing, allow farmers to make long-term investments on their farms in, for example, precision technologies[54].

Finally, educational training launched by the MoA in 2012, known as the 'Pilot Plan for the Training of New Type of Career Farmers', aims to formalise agricultural training, and support the education of farmers in specialist fields, including advanced agricultural technologies. Additionally, it is promoting rural careers and encouraging educated farmers to return to rural communities, thus addressing skills shortages and rural-urban drift[55]. Despite evident innovation in regards to initiatives designed to move Chinese agriculture toward the governments' modernisation goals, and the promotion of precision technologies as part of this process, the focus of these initiatives is not exclusively on technology adoption.

Although providing the pre-conditions to support widespread uptake of precision technologies, adoption in China remains low, particularly across small and family farms that dominate the agricultural landscape. In addition, there is a need to simultaneously maintain the vitality of rural economies and associated livelihoods, help farmers who manage larger areas they have no historical connection to, and consider how best to overcome the fundamental socioeconomic barriers to the wider implementation of agritechnologies. Consideration of these factors is essential in order to facilitate the development and adoption of innovative technologies and farming policies which are accepted by stakeholders and end-users and potentially applicable across different farm scales. This is important from the perspectives of:

- Promoting food security in China.
- Ensuring the resilience and cohesiveness of existing rural social structures.
- Ensuring equitable access to innovative technologies to all potential stakeholders, including those farmers with a stake in small to medium-sized family farms. As part of this, it is essential to address the perceived and actual costs, and perceived and actual social-economic benefits, of adoption relative to income.
- Ensuring sectoral economic growth and local welfare improvements in rural communities through adoption of sustainable intensification practices in agronomy.
- Ensuring that PA technologies will bring improved production practices to the rural economy, as well as having positive impacts upon economic, cultural and social structures in rural communities.
- Establishing how the currently preferred and traditional farming methods can be taken into consideration in agri-technology adoption trajectories.

To date, research conducted to explore the development and adoption of PA technologies has primarily focused on exploring the factors influencing adoption, and there has been limited research that has attempted to provide a theoretical model of both development and adoption to support how innovation is spread through potential end-user communities (the "diffusion of innovations"). The available research has also been conducted in the context of developed countries, and therefore its applicability in accounting for the distinctive contextual factors affecting the rate of adoption of PA technologies in China may be limited. A comprehensive framework, which takes account of these cultural considerations, and also accounts for the different farm scales and structures in China is required.

4 PAFiC framework for accelerated PA development and equitable adoption

4.1 Overview

Many approaches to understanding technology adoption consider the situation of a more or less fully formed technology at the point of commercialisation. A notable example is Rodgers[56] 'Diffusion of Innovation Theory', a cross disciplinary tool designed to explore how, and over what time period, an innovation diffuses through a specific population. In another example, Kuehne et al.[57], provided a quantitative predictive model designed specifically for those planning agricultural research, development extension and policy. The 'Adoption and Diffusion Outcome Prediction Tool (ADOPT) provides a quantitative prediction of the diffusion curve for a given innovation, and provides a means of analyzing the factors influencing adoption. Another more limited literature considers the development stages of technology, from the initial idea through to the point at which it is appropriate to market the end product. This latter process has been characterized by the concept of Technology Readiness Levels (TRL; for example, as defined by the European Commission as part of the H2020 program)[58], that are used to define the development pathway of a new technology. It is based on a 1-9 scale from the preliminary idea and theoretical justification (TRL1) through to regulatory approvals and availability in the market place (TRL9). It has been noted that stakeholder inputs into agri-food technologies are frequently required at earlier TRLs if the technology is to deliver benefits in line with stakeholder priorities and preferences[59].

A framework for PA development and adoption needs to consider development and adoption *in parallel*. Separate assessment of each may lead to:

- An increased likelihood of non-adoption by end-users
- An increase in the time from idea to peak adoption by end-users
- A reduction in the peak level of adoption by end-users

Thus, elements of co-design/development are required whereby interested stakeholders are involved in both development and adoption. Scientists involved in technology innovation need to better understand end-user needs, as well as the process and impacts of technology adoption on (intended and unintended) societal outcomes. End-users need to better understand what can be delivered by the technology, and how the technology can potentially benefit them. Stakeholder and end-user co-production throughout the technology development process may build trust in the technology, and enhance the perceived usability of the technology being developed. In so doing, this approach challenges us to explore the roles of scientists, industry (including manufacturers and SME's), regulators and policy end-users in the innovation process and consider the following questions:

Scientists: can scientists influence the speed and scale of adoption? What changes to their research would be necessary to bring about a given increase in speed or level of adoption?

Regulators and policy end-users: can policies be designed to ensure that technological innovation processes align with end-user requirements and priorities as well as broader policy goals such as improved yields?

End-users: can end-users actively influence the technologies as they are developed in the research process?

Figure 1 below is a depiction of the how the process of co-production of technology development and adoption, when scientists and stakeholders combine forces, affects and enhances adoption leading to more rapid adoption to a higher peak level.

Effective co-designed innovation can help shift the adoption curve to the left (as indicated in red) to speed up the process of *followers* and *laggards* from adopting and

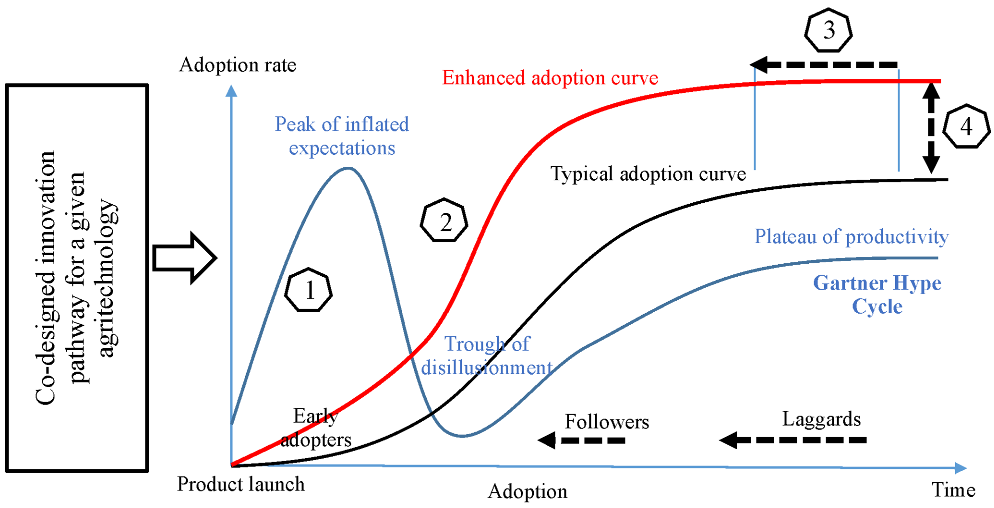

Fig. 1 How effective co-design is predicted to accelerate technology adoption

utilizing new technology. Issues 1–4 are discussed in the text.

The left side of Fig. 1 illustrates how early and effective engagement with stakeholders during technology development will ensure that it is fit for market purpose. A framework for PA development and adoption should enable co-design of the technology to align with stakeholder and end-user requirements and priorities at an earlier stage. This should bring forward adoption by "followers" and "laggards" thus boosting the adoption curve as suggested in Fig. 1, which illustrates:

1) Co-design with end-users in the technology development phase generates reasonable expectations. This reduces the possibility of a new technology being overhyped (e.g., see [60] for a review of Gartners Hype Cycle) and suffering a negative backlash that would likely slow down adoption and reduce the peak adoption level.

2) Consideration of the socio-economic and technical barriers and appropriate extension service type mechanisms (including easy access to real world demonstrations of the technology) enhances the rate of adoption between early adopters and those that follow[61].

3) Twinned with correct policy, regulation and service support, it is anticipated that consideration of both socio-economic and agronomic benefits will lead to reduced time to 'full' market penetration – that is, peak adoption will be bought forward in time.

4) Overall, the process results in greater penetration of the technology and higher rates of adoption (consideration in particular of 'laggard' barriers which are likely to be underpinned by socio-economic not technical issues).

This approach to co-production of agri-food technologies requires the need to adopt the Responsible Research and Innovation (RRI) approach to both the development and adoption of PA technologies throughout the innovation process, not least because this has the power to transform not just the efficient production of food, but also social structures in potentially unintended or unpredictable ways. RRI advocates that affected stakeholders (from scientists and researchers, to end-users including technology adopters, consumers and policy makers) engage throughout the research and innovation process, in order to better align both the process and its outcomes with the needs of all stakeholders. This requires planned engagement and response activities to generate information which can be used to interactively shape technology design along the entirety of the development and adoption timeline. Understanding how current and potential new technologies interact with the needs and aspirations of interested stakeholders is critical to ensuring the acceptability of technologies and accelerate the innovation pathway. Thus it becomes important to co-design developments at different TRLs with stakeholder priorities and preferences, for example through linking end-user needs, their priorities, and preferred usability criteria, at critical points during technology development. This may be an iterative process, such that feedback from end-users continually shapes technology development from early TRLs to TRL9. This may be particularly important if end-users who are not early adopters are to recognize the benefits of technology earlier and adopt it more rapidly. This may require a multi-tiered approach which recognizes difference in adoption characteristics in relation to the differences in, for example, farm scales, agronomic characteristics, and socio-cultural preferences for farming approaches and generation of rural livelihoods.

4.2 Responsible research and innovation

Societal engagement enables the co-production of knowledge, and it ensures innovations address the needs of end-users and the wider society, and captures and anticipates any concerns, value conflicts, and potential regulatory issues in a timely and proactive manner. Effective consultation and assessment of end-user needs and priorities requires adoption of an interdisciplinary approach, with knowledge exchange building on insights gained from social sciences, economics, agronomics and engineering[62,63]. Coles et al.[64], consider RRI to provide a framework for the identification of stakeholder, end-user, and public concerns in an open, transparent way throughout the development and introduction process, and aims to '*foster the design of inclusive and sustainable research and innovation*'[15]. RRI offers broader foresight and impact assessments[65], going beyond ethical assessment, market benefits and risk management[66], encouraging a more inclusive and dynamic process through greater stakeholder engagement and collaboration[65,67], and encouraging greater '*anticipation, reflection and inclusive deliberation*' within the policy making and deliberation process[67].

This approach has been advocated within the domain of PA[31]. Consultation with a broad cross-section of potential users and stakeholders in the design and evaluation stages of new PA technologies is necessary to ensure relevance and compatibility with the target market, especially as the introduction of new agricultural systems and practices potentially impact the dynamics and socio-economic functioning of rural communities. To avoid marginalising potential end-users, it is inappropriate to use a top-down approach. The consideration of the views and agendas of a broad range of stakeholders including, but not limited to, farm managers, laborers, community leaders, policy makers, agronomists, service providers and local communities within the adoption process is essential, and a fundamental component of a framework designed to support the successful diffusion of PA technologies (Table 3). Furthermore, utilizing the methodologies embedded in the RRI process, end-users and stakeholders from early to later TRLs can be engaged as stipulated above.

Table 3 provides an example RRI framework to support accelerated PA development and equitable adoption across varying farm scales, (which represents an ideal range of data which may not be achievable in reality due to pragmatic and resource constraints). The framework illustrates information requirements, including identification of the stage at which this is required in the innovation process, it identifies key stakeholders for engagement in this process, provides an outline of indicative (although not exhaustive) data gathering techniques and associated analytical procedures. Finally, it considers the expected effect on development/adoption trajectories. The framework is intended to prompt collaboration between scientists and end-users throughout the entire innovation process to ensure that technologies meet the needs of the wider communities and societies in which they are embedded. Central to this is the need for interdisciplinary insights to inform technology development and the translational policies that facilitate their adoption trajectories. Ultimately, this should increase the success rates of new technologies and reduce the time between development and peak adoption. Although conceptualised in order to support the adoption of PA technologies on farms in China, the proposed framework has cross-cultural validity and is designed to universally support the adoption of PA, irrespective of geographical location and cultural contexts. Figure 2 summarizes how this framework was validated within the PAFIC project, to support the development and adoption of PA technologies for small farms in China. Note that some elements of the framework may potentially produce outputs that interact with others so that the impact is different for each element of the framework considered in isolation.

One issue relates to how different types of evidence can be integrated (and indeed weighted) in decision-making processes. The argument is that each barrier to PA adoption, whether originating in the socio-economic, broader cultural, technical or agronomic context in which PA in China is embedded, needs to be weighted in terms of potential impacts and managed/responded to within the technology innovation pathway. Similarly, resources need to be directed toward facilitating adoption through the identification of socio-economic factors, which promote farmer and stakeholder acceptance of PA technologies. Incorporating multiple evidence streams into education, engagement and dissemination activities, evaluating end-user responses to these activities, and further refining such activities in response will, first, align PA with end-user and stakeholder needs and requirements and, second, promote end-user strategies which can rapidly respond to changing rural, agronomic and socio-economic environments. This can only be done through the collation of integrated evidence focused on socio-economic, agronomic and cultural drivers of farmer decision-making in relation to the adoption of (different) technologies.

4.3 Application of the RRI framework for accelerated PA development and equitable adoption on small farms in China

The transdisciplinary research project PAFIC provides the basis upon which the proposed framework was developed and through a range of research activities (Table 3) is currently being validated. The PAFIC project provides a case-study illustration of how the integration of evidence streams advocated by the proposed RRI framework will support advanced adoption trajectories of PA technologies in China, and potentially implementation, in order to ensure an effective technology development trajectory. PAFIC seeks to promote best practices for environmentally and profitably sustainable production on commercial family farms in China through improved resource-use efficiency. This aim is achieved by four interlinked

Table 3 An example RRI framework for accelerated PA development and equitable adoption applied to PA adoption in family farms in China

RRI framework element	RRI framework requirement	Stakeholders and timing (i.e., who should be engaged and at what point in the TRL development process)	Research methods	Analysis	Expected effect on development/adoption	Evidence for future policy
Socio-economic barriers to adoption on small farms and relevant communities	Identification of relevant stakeholders and qualitative and quantitative evidence	Early and ongoing engagement with range of stakeholders (TRL-1-9 and post adoption) that are the intended beneficiaries of PA technologies (i.e., farmers and end-users), those with influence over introduction and adoption (i.e., policy-makers at all levels including national, regional and local) and community leaders	Qualitative methods (incl.): - In-depth interviews - Focus groups - Stakeholder engagement workshops Quantitative methods: - Surveys of end-users and stakeholders	- Thematic analysis using qualitative methodologies - Quantitative analysis to distinguish requirements across different end-user stakeholder groups - SEM modeling to assess the relationship between attitude and intention to adopt	- Identification of on farm challenges influencing technology needs and capacity for adoption - Ensuring that technology development aligns with farmer needs - Developing technologies to at least minimum performance needs - Recommendations and translational inputs into policy development	Design measures to overcome barriers to adoption. e.g., - Integrated education and dissemination activities. - Restructure implementation to take account of demographic factors e.g., aging rural population with more women who may not have received technical educations
Identification of socio-economic facilitators of adoption on family farms and relevant communities					- Focus on desired design features that address on farm challenges and farmer needs - Identification of end-user/communities readiness to adopt technologies - Identification of mechanisms to support adoption (i.e., subsidies, agronomic service provision)	- Community/government support regarding technology introduction (e.g., loans/subsidies to communities/farms to purchase/buy in to technology
Assessing ethical issues, including the principal of fairness or equitable access to PA technologies across farm scales					- Appreciation of ethical impacts on local communities (i.e., impacts on rural migration trends, marginalization of poorest farmer, loss of traditional knowledge and farming practices)	- Developing policies to ensure “fairness” or equitable access to PA technologies - Developing policies to preserve traditional farming practice

(*Continued*)

RRI framework element	RRI framework requirement	Stakeholders and timing (i.e., who should be engaged and at what point in the TRL development process)	Research methods	Analysis	Expected effect on development/adoption	Evidence for future policy
Economic impacts of PA technology adoption	Comprehension of the range and variance in economic benefits (costs) in differing farm systems and drivers of benefit/cost	Economic assessments of farmer practice made over the duration of the research project. Baseline through to post implementation assessment and future predictions. Scenario-based assessments of economic impacts under different market conditions Wider economic and Quality of life assessments of impact of adoption on rural communities e.g., impacts on rural liveli-hoods, access to health care and education	On farm partial budget (simplest method which considers effects of varying one input per unit area) to general equilibrium (most difficult and time consuming which considers varying multiple inputs and system wide effects)		- Objective analysis of economic benefits to end users disseminated in optimal fashion - Identification of key financial attributes that drive economic benefits such as farm profitability - Prediction of impact on adoption trajectories under varying market conditions	Key financial attributes that drive economic benefits. For example, cost of PA adoption, impacts on short- and long-term agronomic goals, linked to increased yield and reduced inputs. This can be estimated at earlier technology stages and more formally assessed when the technology is being applied (for example, in developer field trials or during later beta test phases, i.e., TRL 6-9)
Agronomic experiments and interventions to determine impact of PA	Implementation of PA technology solutions aimed at trailing innovations and demonstrating the capacity and benefits of PA technologies on farms and in "real world" environments	Collaboration between scientists and farmers from inception through to prototype trials and final testing (TRL 1-9). Experimental testing in a range of farm environments including demonstration farms on working farms post TRL 9	Technology dependent; specific experiments designed to determine impacts of PA interventions on yield and environmental impacts of farming practices at different farm scales. Assessment of agronomic and environmental impacts of PA adoption in "real-world" environments	Quantitative analysis of improved yields, reduced disease and pest incidence, reduced inputs	- Ensuring the development and promotion of PA technology solutions that are problem focused and align with the needs of farmers - Demonstration of the applied benefits of given technology in a "real world" setting - Opportunity for end-user trial and feedback on design and implementation of technology - Opportunity for adaptions to design to be made post trail to improve adoption rates and time to peak adoption - Assessment of the impacts of PA on existing and emerging environmental policies	- Evidence of reduced agronomic inputs (fertiliser, pesticides, water etc.) following PA adoption - Compliance with emerging environmental standards relating to agricultural production

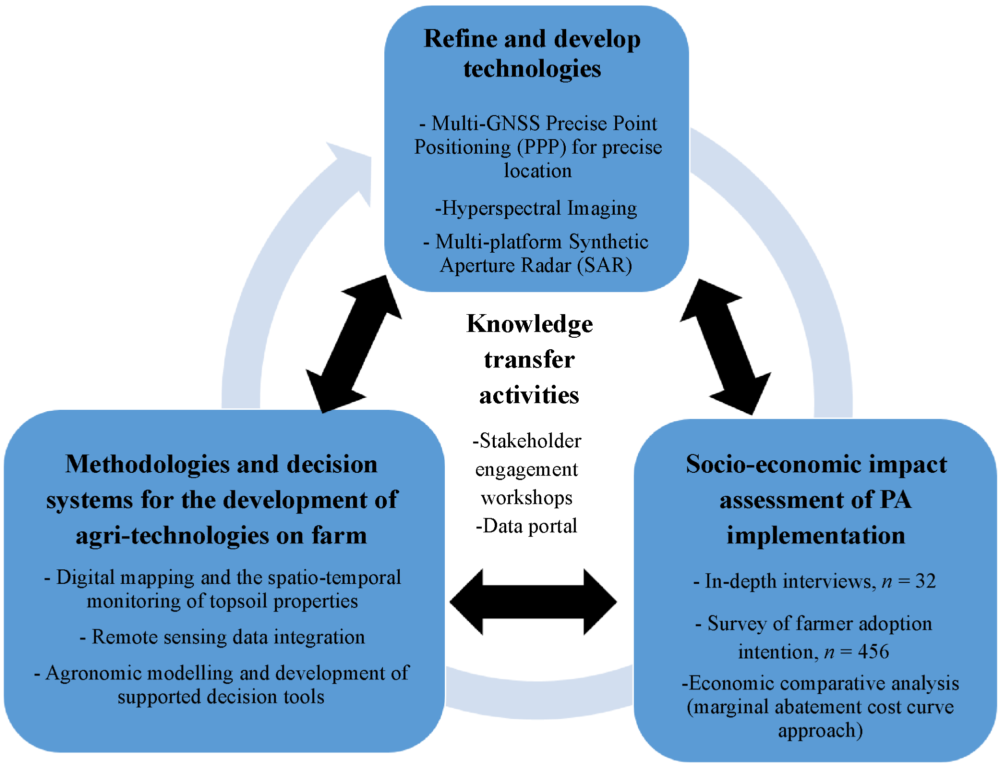

Fig. 2 Application of the RRI framework for accelerated PA development and equitable adoption on small farms in China

objectives that will provide interdisciplinary evidence to support the development of technology solutions and accelerate their translation and on-farm adoption (Fig. 2). An overview of the project is presented to illustrate the context in which the proposed framework was derived and how it is underpinning ongoing research in China which is serving as the basis of the frameworks validation. Findings of the PAFIC project are published elsewhere.

5 Conclusions

The transdisciplinary PAFiC framework for accelerated PA development and adoption will ensure PA technologies are able to deliver sustainable intensification in line with Chinese government policies, while concurrently promoting equity of access to innovation as well as other indicators of social and economic welfare. In addition, a more responsive, adaptive and integrated management of the innovation process[65] will maximise chances of a successful innovation trajectory for applications across all farm scales. Specifically, socio-economic, cultural and agronomic drivers of adoption will be identified to enable determination of how best to implement novel agri-food technologies and this information will be incorporated into education, dissemination and demonstration activities associated with PA implementation. An important result will be that end-user diversity will be mainstreamed into agricultural policy, in particular, but not exclusively, in areas where rural-urban drift represents a barrier to technology adoption (e.g., in relation to gender, and age). The efficacy of interventions designed to improve economic growth and welfare in rural communities will be improved, and the use of agricultural resources targeting agri-research and their application optimised. Finally, the evidence upon which future policies focused on improved sustainable intensification of agriculture and future food security in China will be provided.

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Compliance with ethics guidelines

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