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A TRANSDISCIPLINARY FRAMEWORK FOR 5G AND FUTURE NETWORKS ENABLED APPLICATIONS AND SERVICES INDUSTRY CONNECTION

5G ENABLED AGRICULTURE ECOSYSTEM:

FOOD SUPPLY CHAIN, RURAL DEVELOPMENT, AND CLIMATE RESILIENCY

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ABSTRACT

Agriculture plays an important role in feeding the global population, fostering rural development initiatives, and reducing the overall global carbon footprint for climate resiliency. Furthermore, the agriculture ecosystem spans many industries both urban and nonurban across the globe.

The IEEE SA Transdisciplinary Framework for 5G and Future Networks Enabled Applications and Services Industry Connections (IC) white paper discusses the end-to-end agriculture ecosystem in the context of the food supply chain, rural development, and climate resiliency. A transdisciplinary framework that includes ecosystems, networks, and governance may address the end-to-end agriculture ecosystem in a sustainable and systematic manner. The food supply chain includes the natural environment and resources, food production, processing and packaging, distribution, and consumption. Rural development is discussed within the context of connectivity, cross-ecosystem touchpoints, and local economic development. Climate resiliency is addressed through changes in land use and land cover (LULC).

Numerous opportunities and challenges may be addressed in a phased approach that caters to local priorities, capabilities, and constraints. The transdisciplinary approach facilitates collaboration across different stakeholder groups that strive toward comprehensive solution development across the end-to-end agriculture ecosystem. Potential opportunities include technology innovations, standards development, access to services, economic development, policy development, and resource management.

Keywords: 5G, 6G, agriculture, climate resiliency, connected farm, ecosystems, environment, farming, fishing, food supply chain, governance, indigenous, IoT, land cover, land use, networks, precision agriculture, ranching, rural development, transdisciplinary framework

1. EXECUTIVE SUMMARY

The IEEE SA Transdisciplinary Framework for 5G and Future Networks Enabled Applications and Services Industry Connections (IC) white paper is based on earlier work from the IEEE Future Networks Initiative (FNI) Integrated Network Generations Roadmap (INGR) Applications and Services Working Group [2], [19]. The Transdisciplinary Framework IC intends to engage diverse stakeholder groups to develop actionable frameworks that integrate ecosystems, networks, and governance functions. Stakeholders with a business, technical, or government background may be engaged through a sustainable structured framework that may be used to realize complex functions. This white paper addresses the agriculture ecosystem and its relationships with the food supply chain, rural development, and climate resiliency.

Agriculture may also be viewed as a hub of activities that lead to smart communities. A transdisciplinary framework highlights the food supply chain through specific ecosystem stages or industries that address natural resources, food production, processing and packaging, food distribution, and consumption and recycling. Fixed and mobile terrestrial and non-terrestrial networks may provide the essential communications capabilities through access, service delivery, user and operations management, and relevant network extension components across the ecosystem stages. Connectivity and accessibility [8] are essential access component drivers for rural and remote communities to improve access to services and local gross domestic product (GDP) growth. A strategic rural development vision can be developed through stakeholder engagement and described in comprehensive plans or strategic plans that specifically address local priorities, capabilities, and constraints. Climate resiliency may also be addressed through land use and land cover (LULC) changes during regulatory and policy development. The white paper describes the agriculture landscape with a focus on food supply chain, rural development, and climate resiliency through a sustainable structured transdisciplinary framework that is flexible, scalable, and repeatable. Several opportunities are described that may be addressed in separate initiatives.

2. TRANSDISCIPLINARY FRAMEWORK

The transdisciplinary approach engages diverse disciplines across business, technology, and governance functions. Applications and services across academia, industry, and government are aligned through integrated ecosystems, networks, and governance functions. Each ecosystem stage represents industry group(s) that offer similar products or services. Figure 1 highlights five distinct areas in the agriculture ecosystem that include food production resources, food production, processing and packaging, food distribution, and consumption and recycling. Additional stages may be defined, as needed, to meet the needs of an evolving industry landscape and related industry life-cycle changes within the agriculture ecosystem.

Each ecosystem stage or industry group is aligned within and across different ecosystems and ecosystem stages through key communication network components and technology enablers. The fixed and mobile terrestrial and non-terrestrial network components include access, service delivery, user management and network operations, and network extension functions. Governance approaches include strategic, tactical, and operational functional alignments to meet the local priorities, capabilities, and constraints.

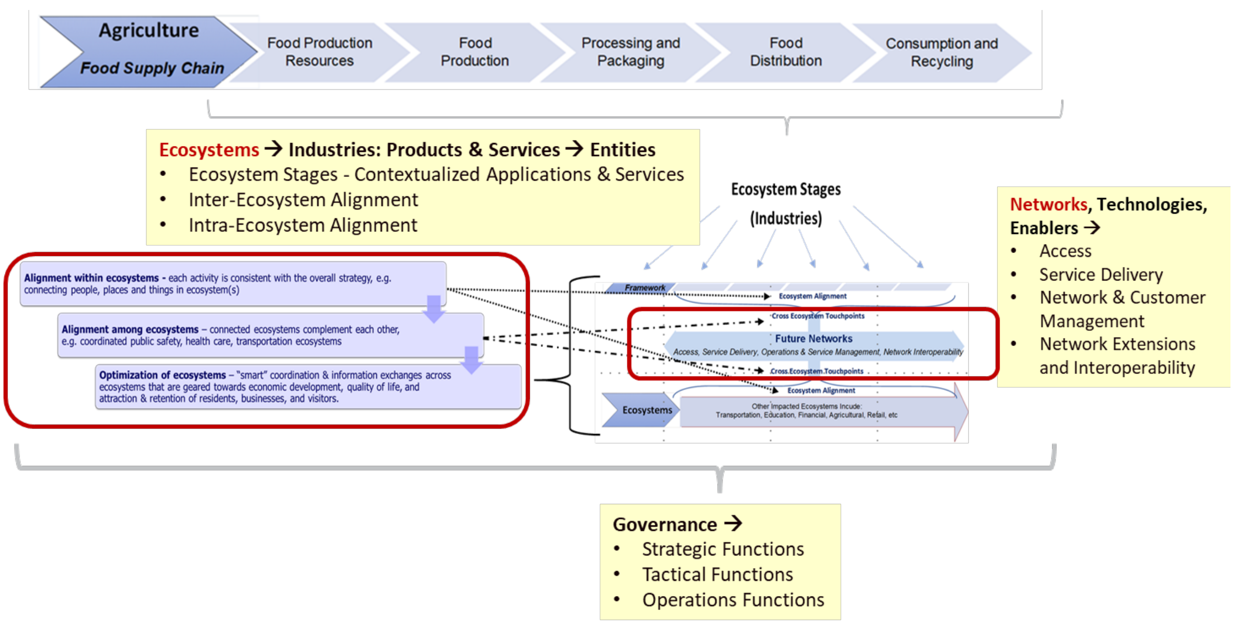

FIGURE 1 – Transdisciplinary approach to the agriculture ecosystem

Agriculture ecosystem stages and cross-ecosystem touchpoints alignments address risks and opportunities across the food supply chain, rural development, and climate resiliency. Agriculture integration with urban and rural communities through the transdisciplinary framework shown in Figure 2 aligns the following:

- **Ecosystem of ecosystems**—Contextualized applications and services within and across ecosystems
- **Network of networks**—Technological convergence and seamless interoperability across terrestrial and non-terrestrial networks
- **Governance function of functions**—Coordinated strategic, tactical, and operations functions

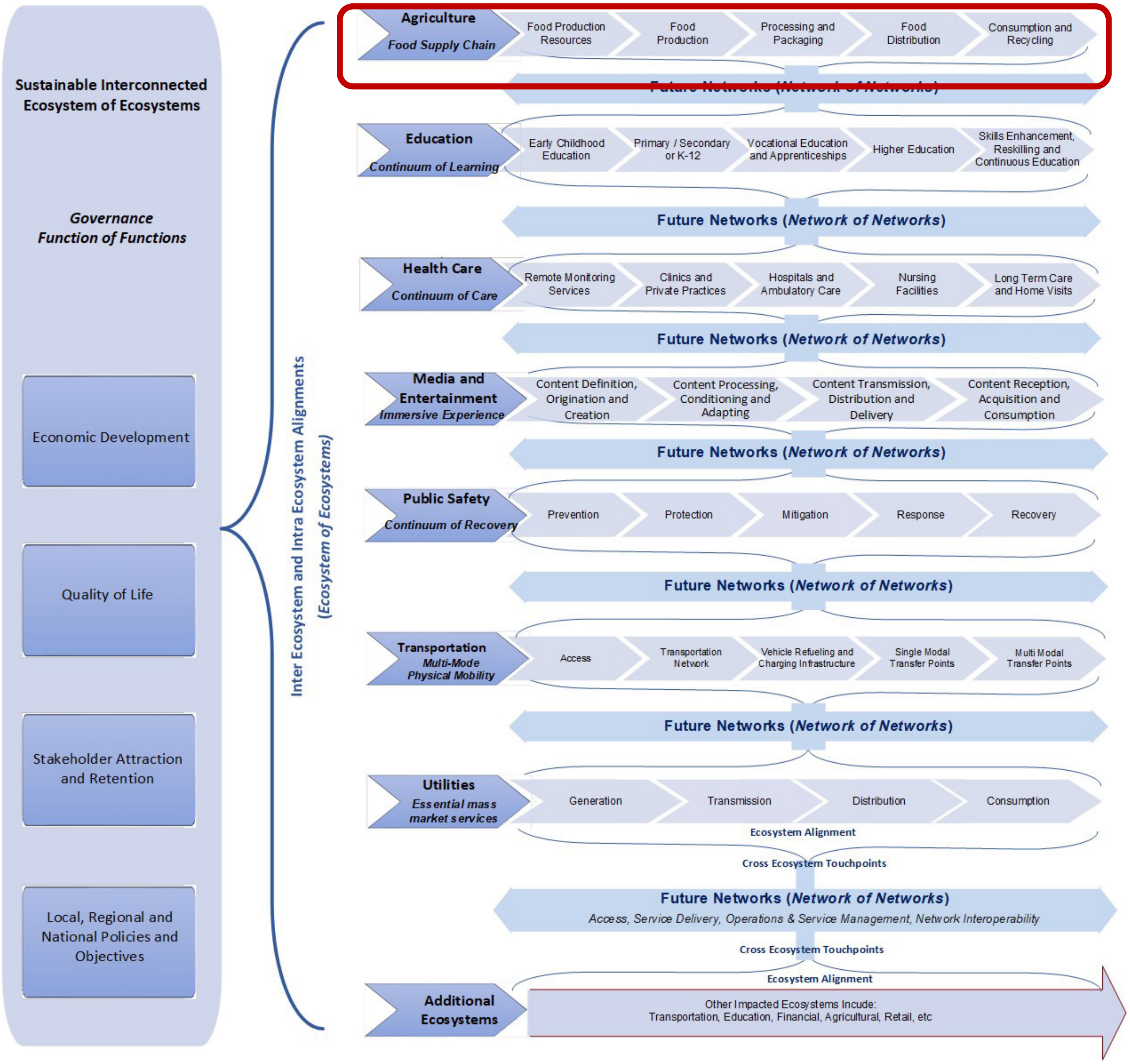

FIGURE 2 – Transdisciplinary framework [2]

The transdisciplinary framework is a sustainable, structured, flexible, repeatable, and scalable framework that can be customized to meet local priorities, capabilities, and constraints. This framework facilitates the systematic discovery of risks and opportunities that include development of new standards, products, or services. Furthermore, this framework can be used to address other ecosystems, such as the healthcare continuum of care [20], technologies for specific public safety mission areas [18], and smart cities [21], for different localized priorities, capabilities, and constraints [24].

2.1. ECOSYSTEM OF ECOSYSTEMS

The ecosystem of ecosystems perspective uses contextualized applications and services and strategic alignments among intra-ecosystem, inter-ecosystem, and optimized ecosystem functions to optimize local capabilities and constraints for specific operational or mission-specific objectives. This approach includes the following:

- **Alignment among the agriculture ecosystem stages**—Each ecosystem stage may be viewed as an industry or a set of industries that provides similar products or services across the agriculture supply chain. End-to-end ecosystem information visibility may be enabled.
- **Alignment among agriculture and other ecosystems—**Ecosystems with aligned stages may regularly overlap and impact other ecosystems, for example, electrified connected vehicles. Therefore, challenges and opportunities arise to identify and address cross-ecosystem touchpoints.
- **Optimization of ecosystems—**Ecosystem stages are combined at their *current operational state* to fulfill specific objectives that may include economic development, quality of life, stakeholder attraction and retention, and area-specific objectives.

The ecosystem and cross-ecosystem stage alignments are shown in Figure 3.

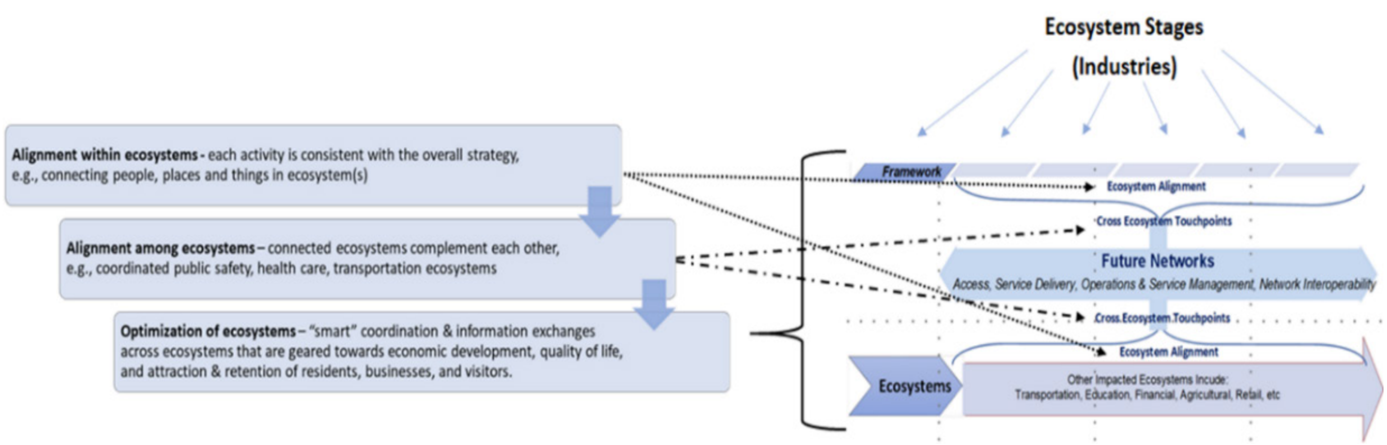

FIGURE 3 – Ecosystem and cross-ecosystem stage alignments

2.2. NETWORK OF NETWORKS

Terrestrial and non-terrestrial networks are generalized into key components as shown in Figure 4 and include the following:

- **Access, for example, radio access network (RAN)**—Ability for a user or "thing" to access the network
- **Service delivery, for example, edge or core network**—Service delivery to/from the user or "thing"
- **Network operations and customer management, for example, business/operations support system (BSS/OSS)**—Customer management and network operations
- **Network extensions, for example, roaming**—Network interoperability with other networks

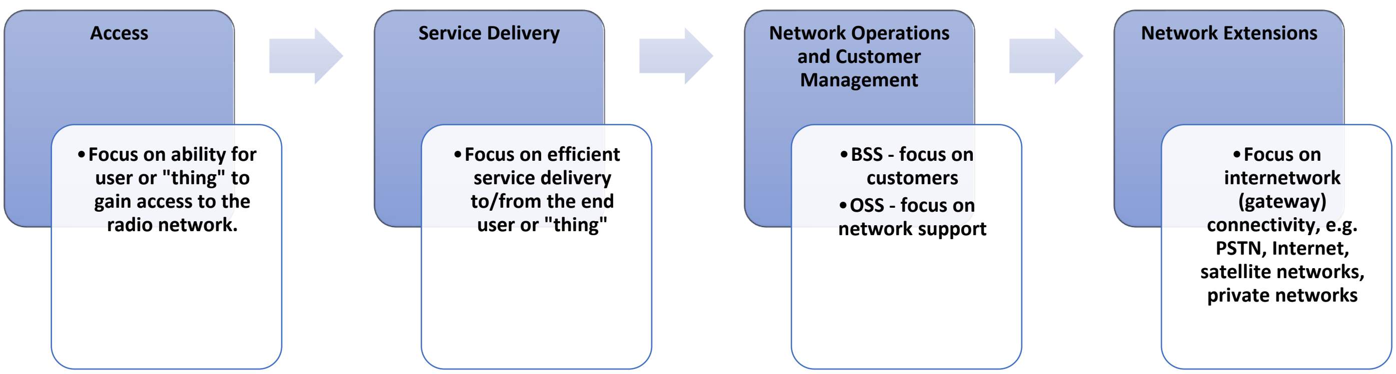

FIGURE 4 – Key network components for fixed and mobile terrestrial and non-terrestrial networks

2.3. GOVERNANCE FUNCTION OF FUNCTIONS

Governance functions are used for complex coordination in which contextualized end-to-end information visibility is essential across the multiple connected supply chains. The governance function of functions approach includes the following combined strategic, tactical, and operations perspectives:

- **Strategic functions**—Includes long-term capabilities planning, strategic positioning within a competitive landscape, and policy development activities

- **Tactical functions**—Includes targeted functions to respond to planned and unplanned events such as pandemics, natural and human-made disasters, large crowds, and so on
- **Operations functions**—Includes information flow for end-to-end visibility and intra-ecosystem and inter-ecosystems necessary for normal operations

3. AGRICULTURE ECOSYSTEM AND STAGES

The agriculture ecosystem is uniquely positioned to address the food supply chain, rural development, and climate resiliency in a coordinated manner using the transdisciplinary framework.

3.1. FOOD SUPPLY CHAIN

The food supply chain extends across the five ecosystem stages: food production resources, food production, processing and packaging, food distribution, and consumption and recycling. Farming, ranching, and fishing are essential activities for the food supply chain. 5G and future networks play a pivotal role in addressing opportunities and challenges in improving food production. For example, the Ohio State University precision agriculture Terra project found that a single 100-acre corn field can generate up to 60.2 TB of data with 2,475 files using 39 different file types through the normal course of growing their crop in an approximate 110-day cycle. A 100-acre field would generate approximately 60 PB of data, which is more storage than 466,000 iPhones and three times more than the amount of data Google processes in a day [28].

5G and future networks promise to enhance the efficiency of the food supply chain through improved yield rates and services. Findings from the FCC Precision Ag Task Force [11] highlight the following areas for improvement:

- Yield gaps from lost crops are based on weather and management decisions.
- Data may be used earlier in the process to improve logistics and tactical decision-making.
- Interoperability challenges include the following:
    - Complex stakeholder groups, for example, farmers, original equipment manufacturers, suppliers (seed, chemicals), service providers, consultants, government agencies, and software/analytics companies.
    - Private and public networks, data, and cloud/edge platforms.
    - Lack of adequate standards.

3.2. RURAL DEVELOPMENT

Agriculture may also help to reduce poverty, raise incomes, and improve food security for 80% of the world's poor, who live in rural areas and work mainly in farming. Agriculture is crucial to economic growth: In 2018, it accounted for 4% of global GDP, and it accounts for more than 25% of GDP for some developing countries [42]. Technologies in the food supply chain create adjacent opportunities and challenges in addressing rural development and climate resiliency. Communication networks and policies that enable connectivity and accessibility also create new opportunities for job creation, local GDP growth, and access to products and services from adjacent ecosystems, for example, healthcare, education, finance, public safety, and entertainment.

Traditional food production activities often occur in rural and remote areas where challenges with communications and local infrastructure exist. Furthermore, the types of services available in a local community are limited. Agriculture, however, has evolved over time and embraced different technologies. By comparison, cellular communications networks and mobile penetration are new, as shown in Figure 5. Therefore, new communications-oriented agricultural opportunities will develop. 5G and future networks promise to deliver seamless terrestrial and non-terrestrial communications capabilities that increase the potential to expand the reach and depth of services in rural and remote communities. Enhanced communications capabilities will also improve access to markets, services, and assets. Local economic development may occur from the ability to openly share the crop health and environmental status that enables the farming community to develop relationships and trust and to achieve better prices for their products.

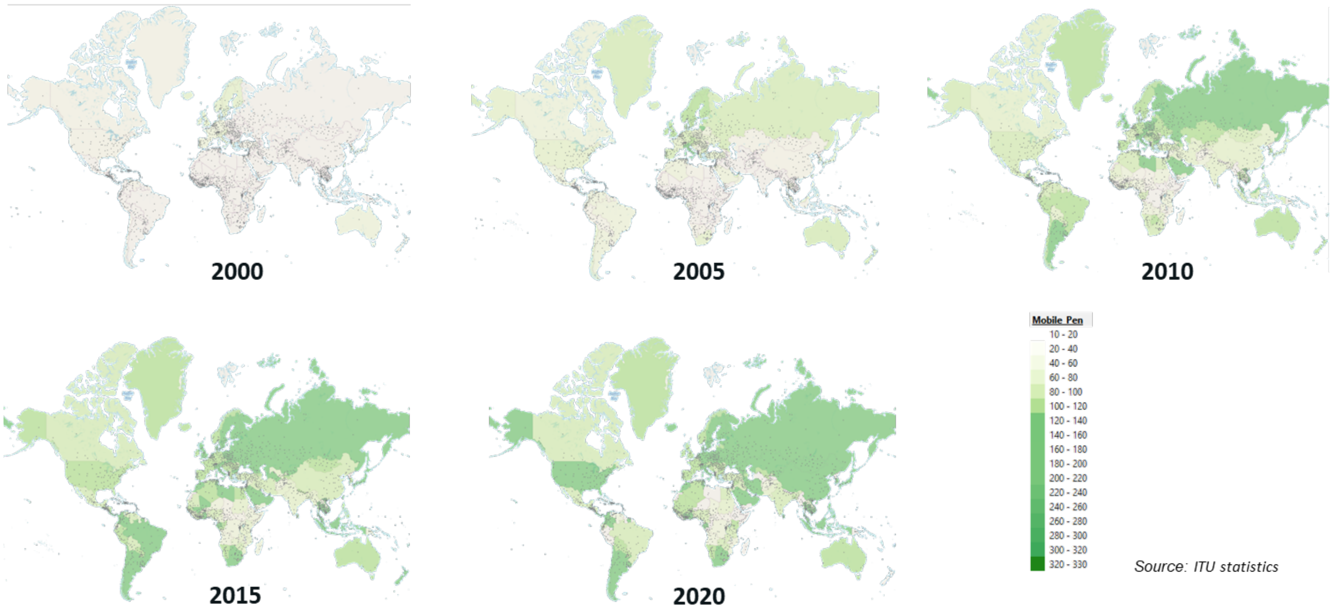

FIGURE 5 – Global mobile wireless penetration rates[1]

Rural and remote communities may plan for a phased approach toward rural development based on local priorities, capabilities, and constraints. The transdisciplinary framework may be used for both rural development and smart cities to address specific objectives described in comprehensive or strategic plans as shown in Figure 6. Cross-ecosystem alignments include applications for mobile financial services, connected vehicles for agriculture, telehealth, and other essential services.

[1] Figure created by uses statistics from https://www.itu.int/en/ITU-D/Statistics/Documents/statistics/2022/July/MobileCellularSubscriptions_2000-2021.xlsx

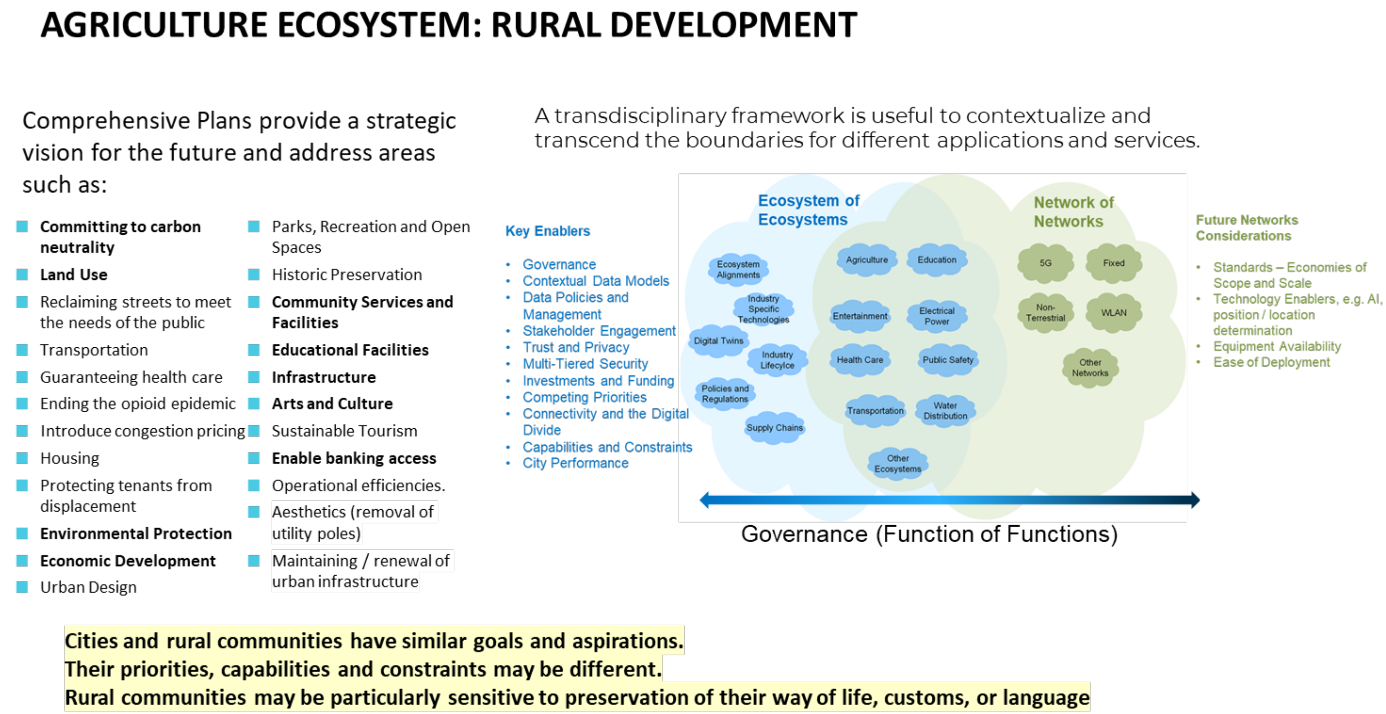

FIGURE 6 – Transdisciplinary approach and comprehensive plans for rural development and smart cities

3.3. CLIMATE RESILIENCY

The NASA Terra and Aqua combined Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Climate Modeling Grid (CMG) (MCD12C1) [27] is shown in Figure 7, comprising various categories that include evergreen needleleaf forests, evergreen broadleaf forests, deciduous needleleaf forests, deciduous broadleaf forests, mixed forests, closed shrublands, open shrublands, woody savannas, savannas, grasslands, permanent wetlands, croplands, urban and built-up lands, cropland/natural vegetation mosaics, permanent snow and ice, barren areas, and water bodies. Land cover may change as a result of environmental factors, human activities, and land use.

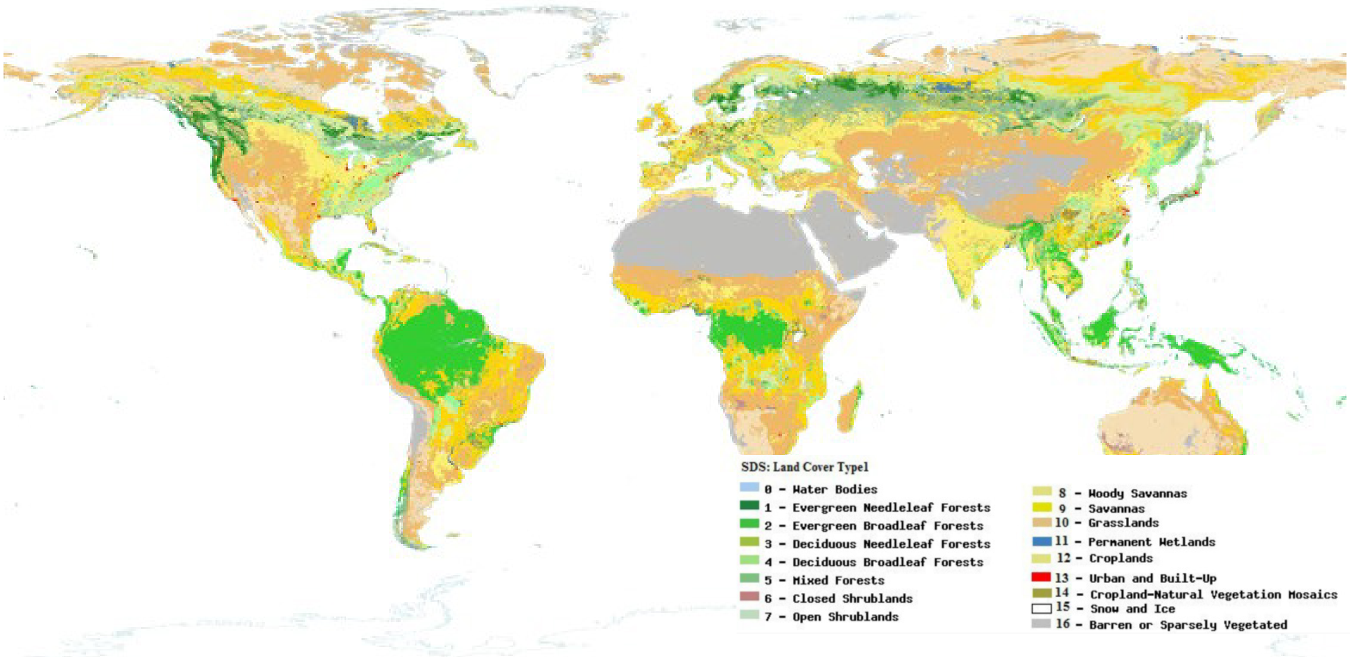

FIGURE 7 – Land cover categories

Agricultural practices vary depending on the topography, soil type, crop type, annual rainfall, and tradition. Land use may influence the field size and geometry,[2] as shown in Figure 8.

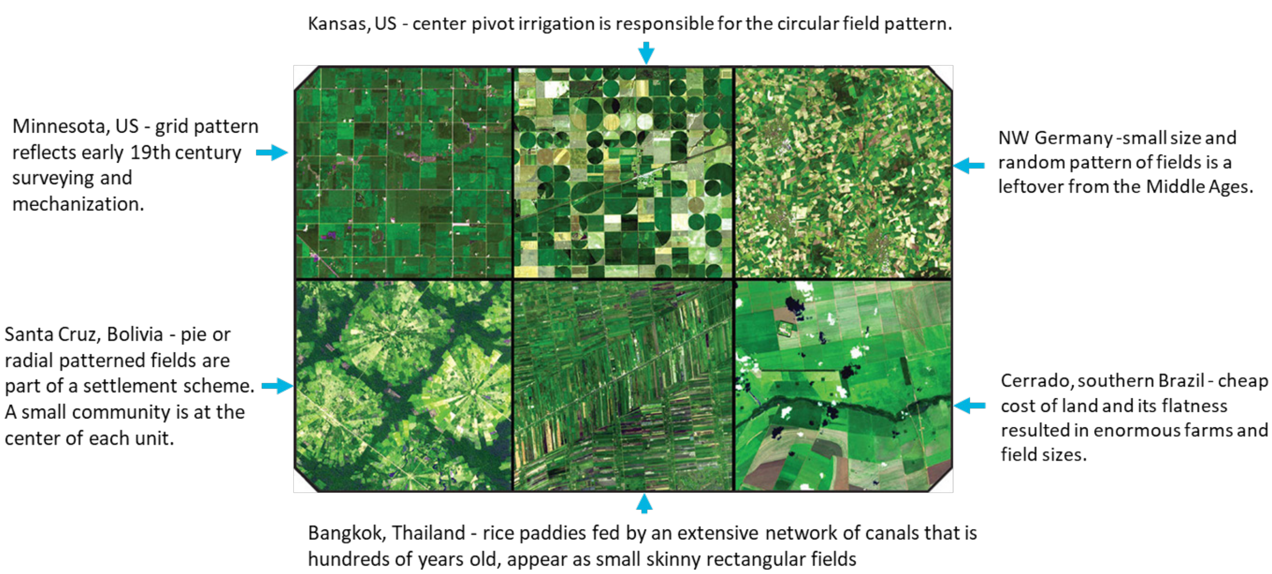

FIGURE 8 – Agricultural practices and land use

[2] NASA/GSFC/METI/ERSDAC/JAROS and the U.S./Japan ASTER Science Team - https://climate.nasa.gov/ask-nasa-climate/434/pick-of-the-pics/

Global food systems are responsible for more than one third of global anthropogenic greenhouse gas emissions. Two thirds of these emissions from global food systems are a result of the land-based sector activities that comprise agriculture, land use, and land cover changes. A whole systems approach to food, nature, and community is needed to protect the collective elements of life: water, land, air, fire, animals, and people [10]. This approach should include a blend of traditional ecological knowledge (TEK) from indigenous communities with other science and management techniques such as controlled or "cultural burn" projects [3], [13]. Both above and below the soil treatments can be addressed together to meet the needs of the food supply chain and climate resiliency.

The GSMA identifies climate-resilient digital innovation agriculture services [16] that include the following:

- **Weather and climate services**—Climate prediction, weather forecasts, and early weather warnings
- **Data-driven agriculture services**—Agricultural intelligence, climate-smart agri advisory, precision agriculture, and early warnings for crop pests and disease
- **Agri-digital financial services (Agri DFS)**—Agricultural credit and agricultural insurance

Climate change also has an impact on critical infrastructure and related ecosystems such as energy, transportation, and healthcare. The effects of climate change are already being felt, with impacts across several sectors, including water resources and food insecurity [9].

5G and future networks may play a critical role in addressing the LULC changes that impact climate resiliency. Applications and services include remote sensing, automated weather stations, Internet of Things (IoT) cloud-based systems, mobile data collection, artificial intelligence (AI)/machine learning (ML), edge services and automation, and geographic information systems (GIS). A transdisciplinary approach can facilitate conservation programs, sustainable agriculture, wildfire and other disaster programs, carbon markets, watershed protection and hydrologic studies, and other governance functions.

4. AGRICULTURE ECOSYSTEM STAGES

Agriculture is the backbone of most economies and the main source of food, income. and employment for rural populations. For instance, in Sub-Saharan Africa and in South and Southeast Asia, 54% and 43% of the labor force, respectively, are active in agriculture and depend on the sector for their livelihoods, and the sector accounts for approximately 15% of regional GDP [15]. The agriculture ecosystem consists of several industry groups that offer similar products and services. These groups are further described along specific ecosystem stages or industry groups that require distinct communications capabilities for service area, capacity, and performance. These industry groups include the following ecosystem stages: food production resources, food production, processing and packaging, food distribution, and consumption and recycling, as shown in Figure 9.

[illegible]	[illegible]
Food Production	Includes farming, ranching, fisheries, and other food sources
Processing and Packaging	Includes the processing and packaging of foods that are generally produced in several geographical areas. Examples include food processing, canneries, etc
Food Distribution	Includes the distribution of food towards the sales channels, e.g., retailers, or end users. This activity may extend beyond a local or national border
Consumption and Recycling	Includes consumer access, food preparation, consumption, and post consumption recycling activities

FIGURE 9 – Agriculture ecosystem stages or industry groups

4.1. FOOD PRODUCTION RESOURCES

Food systems fundamentally depend on natural resources, such as land, soil, water, seed, biodiversity, minerals, biomass, fossil fuels, and climate. Key statistics show that in many cases these resources are not currently managed sustainably or efficiently: An estimated 33% of soils are moderately to highly degraded from erosion, at least 20% of the world's aquifers are overexploited, more than 80% of the input of minerals (e.g., phosphate) do not reach consumers' plates, and 29% of "commercial" fish populations are overfished [39].

The food production resources ecosystem stage includes natural resources and other inputs necessary for food production, for example, land, water, seed, and seasonal temperatures. Networks, technologies, and enablers are needed with communications capabilities across a large service area and support for large volumes of sensors for monitoring environmental changes.

4.2. FOOD PRODUCTION

The Food and Agriculture Organization (FAO) predicts that agricultural product production will need to increase by approximately 70% to meet the demands of the global population by 2050.[3] Sharing and implementation of best practices are needed to realize the full potential of digital agriculture solutions. Horizontal and vertical farming, ranching, and fishing productivity and yields may be increased through tailored information that includes location, type of crop and stage of the farming cycle, local environmental conditions, grazing lands, and so on. Direct access to crop and livestock experts, and medical advice from veterinary and personal health advisories, significantly improves the yield of food production activities.

As mentioned, networks, technologies, and enablers are needed with communications capabilities across a large service area and support for large volumes of sensors for monitoring environmental changes. Improvements in communications capabilities further enable productivity, rural development, and access to external markets and services. These capabilities include both high-tech and low-tech solutions, AI/ML, satellites, sensors, precision agriculture, using data collected by global positioning systems (GPS), satellite imagery, Internet-connected sensors, and other technologies for improved productivity. Although these practices could help increase crop yields and reduce costs, the technologies behind the practices also create opportunities for extremists, terrorists, and adversarial governments to attack farming machinery, with the aim of disrupting food production [14]. Cyber physical systems security capabilities may be improved through cross-ecosystem practices with the public safety ecosystem for the prevention and protection of ecosystem stages [2] and security treatment across different layers (physical, network, and application) [31].

4.3. PROCESSING AND PACKAGING

Food processing has come to be associated with instant noodles, canned meat, and sugary snacks. Processed foods are presumed to be unhealthy. However, food processing provides several benefits as it enables the transformation of raw foods and ingredients into new products such as milling grains into flour, crushing seeds to extract their oil, churning milk into butter, mixing ingredients to make batter, and baking cookies on an assembly line. Food processing also includes the preparation of meat, poultry, egg products, and siluriform fish products that are safe for consumption [40]. Food processing enables a variety of food products and longer shelf lives. Although some food processing techniques use modern technologies such as irradiation and freeze-

[3] "Climate-Smart" Agriculture Policies, Practices and Financing for Food Security, Adaptation and Mitigation Food and Agriculture Organization of the United Nations (FAO) 2010, FAO - "Climate-Smart" Agriculture: Policies, Practices and Financing for Food Security, Adaptation and Mitigation. (fao.org).

drying, other techniques have been practiced for millennia, for example, brewing beer and baking leavened bread in ancient Egypt. Concerns remain over dietary health, worker health, and food safety [6].

Packaging is also important to food preservation and safety. It serves as a barrier against bacterial contamination, pests, physical damage, the elements, and even curious (or malicious) tampering by people. Packaging enables food transportation, storage, and consumption; for example, the spout on a milk carton makes it easier to pour. Packaging also provides a surface for displaying labels, for example, nutritional benefits. However, packaging can contribute to public health and environmental problems.

Food packaging accounts for approximately two thirds (by volume) of total packaging waste in the United States [5]. Discarding packaging materials in landfills has the potential to pollute air and water, whereas burning them for energy can emit greenhouse gases, dioxins, and other pollutants harmful to public health and the environment. Recycling, composting, and reusing containers offers more environmentally sound alternatives. Manufacturers can also reduce the amount of food packaging material, ideally without compromising benefits to consumers.

The food production resources ecosystem stage includes the processing and packaging of foods produced in several geographical areas. 5G and future networks provide additional capabilities to address these concerns through the ability to monitor food processing, packaging, food safety, and inspections for meat, poultry, and egg products; worker health and safety; social vulnerabilities based on dietary access and health; and so on.

4.4. FOOD DISTRIBUTION

Food distribution provides a link between producers and consumers. The food distribution network includes food producers, wholesalers, distributors, warehousers, and business and private consumers to meet the needs of the agriculture supply chain along the ecosystem stages described in the transdisciplinary framework. Individual farms, ranches, or fisheries will likely not produce enough variety or volume to serve a large business or pools of rural or urban customers. Gaps in the food distribution network could mean that some areas may not have access to fresh produce, for example, urban food deserts.

The food distribution network addresses these needs through large food aggregation, storage, and intermodal transportation capabilities. Food distribution within the agriculture ecosystem may include transportation across large distances because of the location of large producers, lower prices, high demand for large urban populations, seasonalities, and environmental conditions. Individual producers may use separate distribution networks to reach consumers directly and build local relationships, for example, farmers' markets.

Communications networks enable efficiencies and intra-ecosystem alignments along the agriculture ecosystem stages and subsequent supply chain networks. Inter-ecosystem alignments introduce new capabilities through cross-ecosystems touchpoints, for example, transportation, manufacturing, and the financial ecosystems described in the transdisciplinary framework. 5G and future networks enable end-to-end supply chain management efficiencies.

4.5. CONSUMPTION AND RECYCLING

The availability, quality, variety, and affordability of food that meets the needs of local areas impacts the rate and volume of food consumption. People in low-income countries derive nutritional energy mainly from carbohydrates; the contribution from fats is small, that from protein is the same as in high-income countries, and the use of animal sources for meat and dairy is negligible. People in high-income countries derive nutritional energy mainly from carbohydrates and fat, with a substantial contribution from animal sources for meat and dairy. Food consumption shows similar patterns in areas with economic growth. This trend may lead to pressures on natural resources because of the change in food demand and consumption [12].

The food consumption and recycling ecosystem stage includes consumer access, food preparation, consumption, and post consumption disposal or recycling activities for a "return to earth." 5G and future networks provide additional capabilities to address social vulnerabilities and access to basic food supply, including fresh produce in urban areas or areas with food shortages. Nutritional information may be communicated through education programs that may be delivered digitally. Trends in consumption and subsequent impacts to natural resources could lead to alternative food sources such as plant-based substitutes, and so on. This information may be used to influence the food production cycles and the food supply chain.

5. NETWORK OF NETWORKS

Communication networks play a key role in extending the reach and depth of the agriculture ecosystem and applications and services to address the food supply chain, rural development, and climate resiliency. Key considerations for communication networks include the following:

- **Capacity**—Large data volumes are provided for GIS, high-definition satellite and drone imagery, and large amount of network data points.
- **Data network symmetry**—Both downlink and uplink capacity are needed for decisive data inputs and outputs. High-capacity and low-latency services support auctions.
- **Reliability**—Producers may need to take timely critical actions for resources such as fuel, feed, water, domestic animals, fertilizers, herbicides, and pesticides.
- **Scalability**—Networks should be scalable to address growth, exponential increase of devices and data volume, and operational costs.
- **Security—**Increased digitization creates new risks from hackers and terrorists to attack this equipment by exploiting network, system, and application vulnerabilities. Security measures include regular backup, air gap, network segmentation, multifactor authentication, cybersecurity awareness, and training.
- **Investment**—Mobile networks deployment drivers include population density, building density, vehicular traffic, revenue potential, and investments. Rural areas do not tend to have multiple providers because of the high investment costs and potential market revenues.

Fixed and mobile terrestrial and non-terrestrial networks are generalized into key component functions for the following:

- **Access**—Includes end-user devices, such as sensors, spectrum, antennas, cell sites, RAN facilities, including deployables and fronthaul/midhaul/backhaul transport.
- **Service delivery**—Includes edge/core categories such as edge computing, network function virtualization (NFV), software-defined networking (SDN), core network control and user plane functions, core network sharing, network performance, preemption, internal clouds, and network slicing. Additional network operations enhancements include enhanced vehicle-to-everything (eV2X) aspects, extreme long-range coverage in low-density areas, network capabilities exposure, and so on [1].
- **Network operations and customer management**—Includes OSS/BSS, dynamic policy/network configurations, service-level agreements (SLAs), application programming interfaces (APIs), device management, (inter)national roaming support, network/element management system (NMS/EMS), billing, and so on.
- **Network interoperability**—Includes network interoperability, seamless technology change,

external roaming support, ecosystem specific networks, and so on. Network operations may use virtual roaming hubs and realms to enable network interoperability.

These network components may be used to enhance the agriculture ecosystem and the food supply chain, rural development, and climate resiliency activities, as shown in Figure 10. Each ecosystem stage has different service area, capacity, and performance requirements that can be dimensioned according to the four key network component area functions. For example, different requirements exist for farming or food production and an indoor facility that processes food. These requirements are realized through specific access networks, edge services, third-party providers, and roaming arrangements. Figure 10 shows the conceptual relationship among the terrestrial and non-terrestrial access networks that use different options for interoperable communications, for example, access point names (APNs) among networks or through the public Internet. Governance functions are described in the red boxes on the outer edges of the graphic. The combined ecosystems, networks, and governance pillars are used to increase the reach and depth of agriculture products and services.

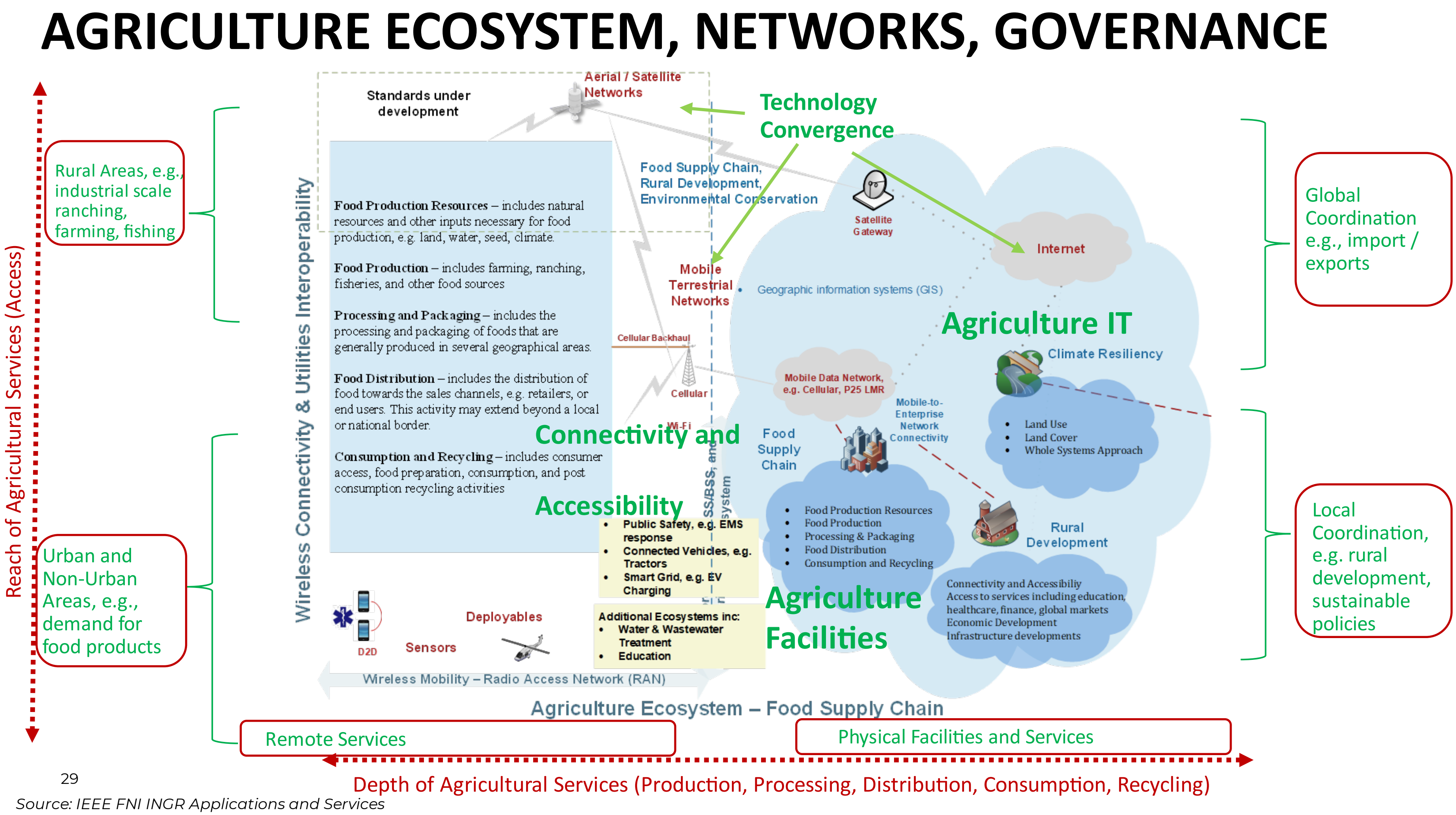

FIGURE 10 - **Transdisciplinary framework for the agriculture ecosystem: Food supply chain, networks, and governance [2]**

5.1. ACCESS

Terrestrial and non-terrestrial networks may be used to provide communications access for farming, ranching, and fishing production activities. The service area, capacity, and performance requirements for access networks enable smart operations for ecosystem stage functions. For example, a connected farm in the food production stage may have the following elements:

- **Tractors**—Crop care functions such as tilling, planting, and cultivating
- **Seed tenders**—Seed accountability and traceability as they are planted
- **Sprayers**—Plant protection via fertilizers, and so on
- **Spreaders of fertilizer or manure**—Disperse crop inputs (and creating records)
- **Irrigation systems**—Disperse water to growing crops
- **Combines and harvesters**—Crop harvesting, for example, records of yield and traceability records
- **Grain carts**—Receive and transfer harvested crops into trucks to begin processing
- **Feed mixers**—Receive and mix ingredients, and transfer rations to livestock, for example, cattle
- **Grain elevators**—Receive and distribute grains (also enables food traceability)
- **Grain handling and drying facilities**—Monitor soil moisture, crops, and product traceability
- **Wearables**—Monitor livestock, for example, cows and large animals, for health and activity tracking
- **Feeding barns and watering troughs**—Livestock
- **Milking parlors**—Support milking process for dairy cattle
- **Milking systems**—Semi/autonomous systems (also records volumes and cycle times)
- **Drones with cameras and 5G connectivity**—Real-time image recognition-based system for individual dairy cow monitoring, behavior analysis, and feeding
- **Solar-powered robotic devices**—Autonomously treating and removing weeds
- **Autonomous crop pickers**—For ripe fruit and vegetables

The network service area may be limited in rural and remote areas and require non-terrestrial services from satellite or aerial network nodes such as high/low-altitude platforms (HAPs/LAPs), unmanned aerial vehicles (UAVs), and drones. User equipment, sensors, and other IoT devices can access the terrestrial and non-terrestrial networks. Access networks may include LoRaWAN, Sigfox, NB-IoT, Wi-Fi, ZigBee, cellular, and satellite. Digitalization and robotization may aid sensor placement to retrieve data on yield, soil, and fertilization [22]. However, sensors have a low battery capacity and may need to be charged periodically. UAVs may be used to charge sensors through wireless power transfer and to retrieve sensor data [7].

Sustainability has always been the farmer's objective. Precision agriculture has the potential to elevate the farmer's ability and make the notion of "farm to market" more efficient and productive. The utilization of IoT sensors can transform farming by connecting and integrating everything in the farming process, from soil management and animal production to irrigation systems. These sensors can further be used to control better the farming environment, temperature control, soil condition, contaminants, and water quality. This technology can provide a wide range of enhancements that can create new opportunities for farmers. The evolution of 5G and beyond offers the possibility to develop innovative farming and eliminate waste across the farming process. 5G-Advanced and next-generation 6G technology will provide fast and high-volume data connectivity to support the digital transformation, act as a catalyst to improve social vulnerabilities, and enable new agriculture applications and services. Improved communications capabilities would enable additional potential for rural development and access to basic services, for example, access to telehealth services and the continuum of care [20].

5.2. SERVICE DELIVERY

Service delivery includes specialized equipment and capabilities required to support different applications and services in the ecosystem stage. The service delivery model would provide abstraction for (1) physical produce, (2) equipment used, and (3) the activities performed to automate most of the elements required. For example, plucking of apples may involve drones along with tractor-mounted robotics arms and a trailer for carrying the plucked harvest. In addition, an innovator may offer drones with the ability to pluck apples from hard-to-access parts.

Such solutions would be deployed on virtualized computing platforms using composable applications that leverage the connected computing platforms in conjunction with available resources. Besides improving resource utilization, these services would be deployed and de-commissioned on demand. Some elements of the solutions also likely would move across geographies based on seasonal demands.

Next-generation orchestration platforms enable dynamic discovery of physical and virtual resources to offer the services. For example, application-level orchestration may involve (1) discovery of a drone's availability and capability (flying time, camera, available fuel, last serviced date, etc.) rented from rural entrepreneurs; (2)

deployment in conjunction with harvesters/tractors and truck/trolleys co-shared by the village community for optimal harvest (or deweeding or irrigation); and (3) subsequently storing the harvest in a local air-conditioned warehouse. Based on the supply chain inputs (or farmer's preference), only a subset of the product may be harvested to optimize the returns for the product.

Service delivery functions may also be used for leaf disease detection and mitigation. Image processing-based ML techniques may be used to detect and control hazard spread, such as a leaf disease detection remote monitoring system overseeing the server, moisture, temperature sensing, and soil sensing. Soil quality monitoring may be used to prevent leaf diseases from insects and pathogens. AI also helps to identify and classify leaf diseases. After an infection is identified, the soil parameter values such as moisture, humidity, and temperature, and the chemical level in a container, can be delivered to farmers through mobile applications. Relays may then regulate the motor and chemical sprinkler system as required through the mobile application. AI/ML solutions can provide an efficient method to detect and control the spread of various leaf diseases and improve yield rates [26].

AI and data analytics can analyze massive amounts of data obtained from drones, IoT, and other measuring instruments. Historical information for the farm and weather data may be integrated to optimize all stages of the production process, for example, fertilizer and pesticide application with surgical precision, crop harvesting based on color and size, irrigation systems, crop disease and quality, and yield improvements. A massive increase in computing power and data collection are the driving forces behind the rise in AI. However, artificial intelligence requires adequate data to work efficiently. 5G will speed up a large amount of data transfer to meet the need for analysis, which will help AI perform efficiently.

5G and future networks, IoT, big data, and AI may also be used to increase labor productivity and reduce reliance on foreign labor, increase the productivity of crops, and the effectiveness of land usage to increase palm oil yield. However, areas with inadequate communications service areas are obstacles to the adoption of 5G capabilities [32].

The 5G enabled IoT-based cloud computing service allows for automated operation of various unmanned agricultural machines to ensure plowing, planting, and management of crop farming. This service could also lead to secure, reliable, environmentally friendly, and energy-efficient operations and the creation of automated farms [33]. 5G, IoT, and mobile edge computing (MEC) enables robots and automated systems to execute tasks on a collaborative and daily basis for assisted farming. Low-latency communication capabilities are required for robotic-aided smart agriculture vision [41]. Network slicing with 5G quality indicators (5QIs) for precision agriculture can address very high data rates, near-to-zero latency, and a huge density of devices. 5G-Advanced and future 6G mobile networks may be used to extend the depth of precision agriculture features [34].

GPS and GIS technologies enable the coupling of real-time data collection with accurate position information. The localization precision of GPS is 3 m and 5 m, which is inaccurate for plowing topsoil in a field. Real-time kinematic (RTK) technology can be used to provide an accuracy of less than 3 cm. 5G relays the corrected high-precision position data in real time to vehicles, drones, and autonomous machines to stay precisely on track.

Several challenges and opportunities are related to service delivery capabilities for agriculture applications and services. They include network softwarization techniques such as SDN, NFV, cloud computing (CC), edge computing (EC), 5G network slicing, and the associated system optimization, orchestration, and management mechanisms. Service delivery challenges include open standards for SDN and NFV, resource autoscaling for cloud computing, resource management and performance for edge services, and RAN implementation support and security provisions to support network slicing [29].

5.3. NETWORK OPERATIONS AND CUSTOMER MANAGEMENT

Network operations and customer management functions enhance the customer experience and network health. This enhancement may include improving capabilities for governance functions such as policy development realization, data model governance, third-party providers, APIs, and network exposure functions. Equipment vendors, agriculture supply chain vendors, and communication and cloud service providers would drive standardization of (1) equipment onboarding; (2) automated service offerings; (3) integration with other “ecosystems” such as finance, transport, retail, or storage; and (4) servicing and maintenance of the network. Increasing application of AI/ML aspects in operations would reduce the need for experts in routine management and operations activities.

Remote sensing as an essential function can address elements of the food supply chain and climate resiliency. It may be used for sustainable agriculture and to estimate plant physiological features. A cooperative anti-interference mobile edge computing strategy that includes MEC, IoT devices, and UAVs may be used to provide higher spectral, spatial, and temporal resolution imageries. AI/ML and big data applications are needed to process the enormous amounts of data generated from remote sensing [25]. The LULC information may be provided to stakeholders along the food supply chain.

Third-party providers may provide security services along the ecosystem stages. For example, an image electronic fence for smart farms based on image recognition and sensor fusion technology may be used to prevent crop theft, minimize the need for farm labor, and intelligently monitor crop growth [17]. Cameras and beacon tags may be used to determine whether individuals entering or exiting the premise are authorized. 5G and future networks may enable the high-speed and low-latency transfer of video and beacon detection data. Cross-ecosystem functions with the public safety ecosystem may increase alignments and seamless functionality.

5.4. NETWORK EXTENSIONS (INCLUDES INTEROPERABILITY, ROAMING)

Network extensions include network interoperability and (inter)national roaming functions that may include extended support for financial and technical data exchanges for vehicles and equipment that span different networks and service areas. Next-generation networks (5G and beyond) allow for heterogeneous network connectivity options. Private networks have become increasingly common in industry, and some of them can be templatized for agriculture. New hierarchical satellite architectures [30] and 5G integrated architectures [23] promise to extend the reach and depth of future networks enabled agriculture solutions. Interoperability among networks includes intersystem connectivity through access point names (APNs), interworking functions, and bilateral and hub-based roaming architectures to support home-routed and local breakout roaming scenarios.

The farm equipment would extend from Industry 4.0/IoT and expose additional capabilities and control points. Turnkey solutions would help develop targeted applications using the next-generation precision agriculture equipment. The financial aspects such as loans/insurance/billing and settlement of most of these services would also be created in the context of the templates.

Blockchain enabled services may be used in each stage of the food supply chain to enable transactions related to network extensions. These services secure, monitor, and analyze agricultural data. Blockchain is dependable, immutable, transparent, and decentralized, and it may replace the traditional method of storing, organizing, and exchanging agricultural data. IoT and blockchain may be used to extend the smart farm to an essential component of the food supply chain that can provide a greater degree of autonomy and intelligence.

Security and privacy issues may need to be addressed for the development of blockchain-based IoT systems [35].

New business model opportunities along the food supply chain could emerge as challenges related to interoperability, security, privacy, data governance, and cultural shifts are addressed [4].

6. GOVERNANCE

The United Nations (UN) defines "good governance" as the process of decision-making and the process by which decisions are implemented. The UN's list of eight characteristics for good governance are participation, consensus oriented, accountability, transparency, responsiveness, effectiveness and efficiency, equity and inclusiveness, and rule of law [38].

Governance models combine policies, systems and structures, and strategic and operational frameworks, and they describe the interaction among actors in the authority chain. The transdisciplinary framework describes the governance for the following:

- **Strategic functions**—Long-term capabilities planning and strategic positioning
    - Examples may include data governance models, phased transition and repurposing of assets, urban mobility pilots, and policy development.
- **Tactical functions**—To respond to planned and unplanned events
    - Examples include pandemic response, natural and human-made disasters, and cross-ecosystem coordinated response through emergency support functions.
- **Operations functions**—Intra-ecosystem and inter-ecosystems information flow necessary for normal day-to-day operations
    - Examples include city performance metrics (or key performance indicators [KPIs]), city operations, and stakeholder outreach.

6.1. STRATEGIC FUNCTIONS

Strategic functions include long-term capabilities planning, strategic positioning within a competitive landscape, or developing pilots to determine strategic goals. Examples of strategic functions include efficient alignments along the agriculture supply chain for ecosystem stages, alignments among different ecosystems for rural development, and near-term and long-term policy developments to support climate resiliency. 5G and future networks may provide additional capabilities to address strategic functions that include resource conservation programs; food supply chain inspection programs; data governance models that include security and privacy along the ecosystem stages; digital inclusion and digital literacy programs; and carbon emissions reduction programs such as soli carbon monitoring, funding, and investment. The ecosystem stages and network capabilities described earlier may be used to develop a strategic roadmap for the food supply chain, rural development, and climate resiliency. This roadmap may address local priorities, capabilities, and constraints that may be addressed in comprehensive or strategic plans.

Strategic functions and roadmap developments may also be used to address the UN sustainable development goals (SDGs) [37], as shown in Figure 11. Coordinated strategic agriculture initiatives towards the food supply chain, rural development and climate resiliency can lead to SDG goal fulfilments for local communities. The food supply ecosystem stages can aid in the development of shaping or adapting strategies across the end-to-end ecosystem. The network of networks and the four key network components enhance the ability to realize the strategies for the tactical and operations functions discussed next.

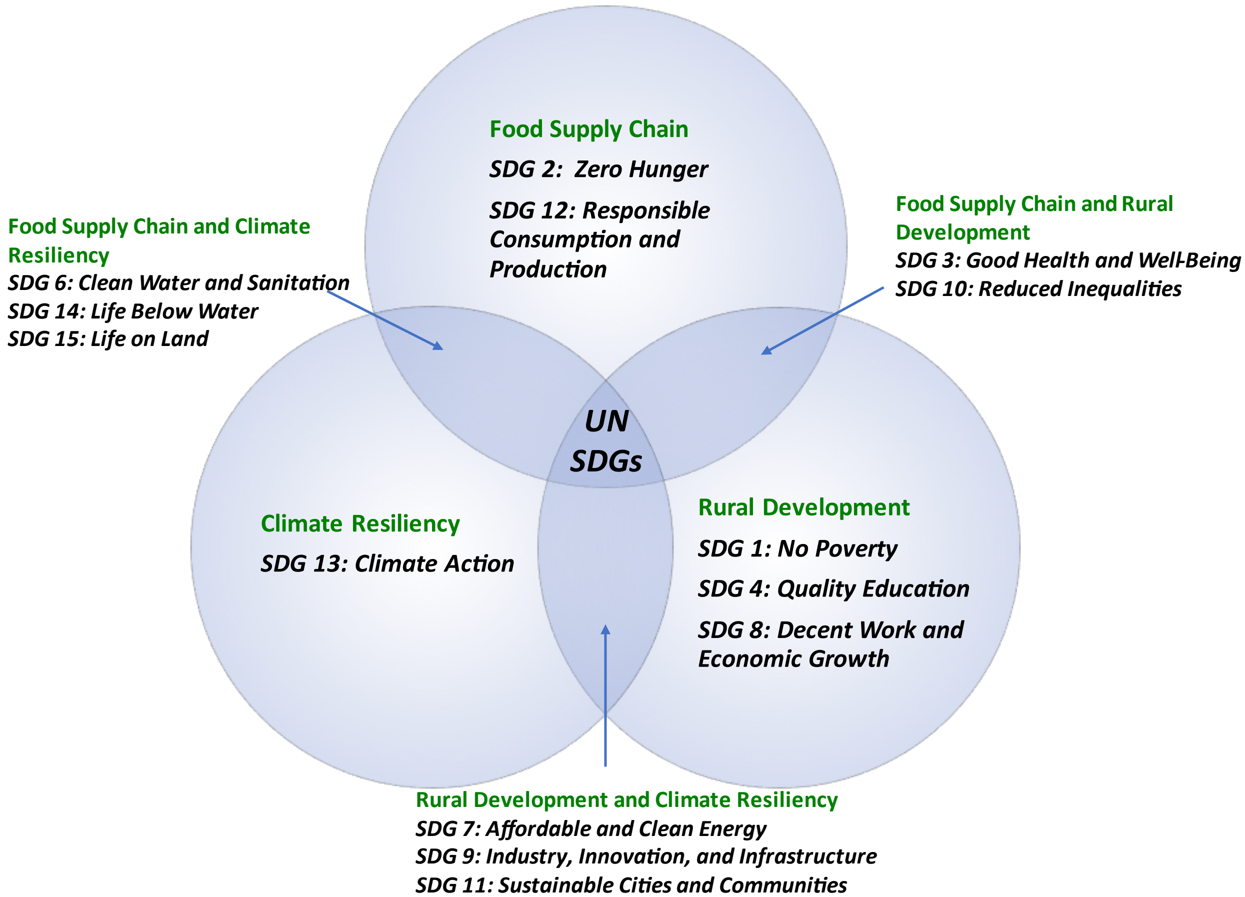

FIGURE 11 – UN sustainable development goals (SDGs) and the agriculture ecosystem

6.2. TACTICAL FUNCTIONS

Tactical functions include targeted functions to respond to planned and unplanned events such as pandemics, natural and human-made disasters, and agriculture information and communications technology (ICT) pilots and deployments. New initiatives require changes to introduce new technologies and the necessary changes in the processes that need to be carefully planned and executed. 5G and future networks may provide additional capabilities to address tactical functions that support food inspection events and foodborne outbreaks across the ecosystem stages, adverse weather events that may impact the food supply chain especially the food production functions, and so on. Performance and lessons learned in tactical responses may be used to develop new capabilities or augment current capabilities.

The level of performance for operations functions acts as a baseline of capabilities for tactical functions.

6.3. OPERATIONS FUNCTIONS

Operations functions include the information flow for end-to-end visibility and intra-ecosystem and inter-ecosystems necessary for normal operations. The typical network deployment stages for planning, deployments, operations, and decommissioning of obsolete functions would apply for a sustained operations functional perspective.

The operations functions include the optimized level of performance based on the current state of each ecosystem stage implementation in a local area. Each ecosystem stage, when coupled with available network capabilities, may vary in its level of available services and geographical reach. Furthermore, local constraints, for example, financial considerations, may impact the operational capabilities from one local area to another local area. 5G and future networks may provide additional capabilities to address operations functions that address real-time data capture, field operations, analytics, traceability, data sharing, budget monitoring and control, performance metrics, observance of relevant standards, and so on. Agriculture also contributes to greenhouse gas emissions. Operations functions may include the monitoring of nitrous oxide emissions from soils, fertilizers, and manure from grazing animals; and methane production by ruminant animals and from paddy rice cultivation [36].

7. RECOMMENDATIONS AND SUGGESTIONS

This white paper addressed the following key opportunities and challenges related to the agriculture ecosystem:

- Agriculture has the potential scope to address the food supply chain, rural development, and climate resiliency.

- The transdisciplinary framework for 5G and future networks enabled applications and services can be used to align the agriculture ecosystem stages and food supply chains, align across ecosystems for rural development, and align with governance-related initiatives to address climate resiliency:

    - A detailed analysis of each ecosystem stage through the key network component perspectives may yield opportunities and gaps that can be addressed through strategy, tactical, or operations functions. New standards development or existing standards enhancements is one method to promote strategic goals for economies of scale and scope.

- Agriculture may also help to reduce poverty, raise incomes, and improve food security for poor and developing countries or regions. Communication networks and policies that enable connectivity and accessibility also create new opportunities for job creation, local GDP growth, and access to products and services from adjacent ecosystems, for example, healthcare, education, finance, public safety, and entertainment.

- Multiple opportunities and challenges exist in each agriculture ecosystem stage related to networks, technologies, and enablers. They include connectivity and accessibility, blockchain enabled transactions, rural development initiatives, climate resiliency, and new standard developments.

- Network softwarization techniques include SDN, NFV, CC, EC, 5G network slicing, and the associated system optimization, orchestration, and management mechanisms. Service delivery challenges include open standards for SDN and NFV, resource autoscaling for cloud computing, resource management and performance for edge services, and RAN implementation support and security provisions to support network slicing.

- A blend of TEK and other science and management techniques for above and below the soil (or surface) treatments may be integrated to meet the needs of the food supply chain and climate resiliency.

- KPIs may be defined for strategic, tactical, and operations agriculture functions for the food supply chain, rural development, and climate resiliency.

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