The "4D" Revolution in Livestock Production:

The Advent of Precision Livestock Farming (PLF) through a Synthesis of Diagnostics, Devices, Digital Platforms and Data Analytics

> *"The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it."*
>
> Mark Weiser[1]

The "4D" Revolution in Livestock Production: A Context

How livestock production, health and welfare are done will radically change over the next decade. To be clear – the timeless goals of producers, veterinarians and others engaging the value chain of livestock and protein production will remain virtually the same – business profitability, accountability to consumers and a shared responsibility for the care and welfare of the animals will continue to be our collective aim. What will radically change, however, will be both the means by which these goals are pursued/achieved, and the mindset of us all towards adopting and adapting new ways to pursue and achieve them.

The same basic conditions and drivers that are now changing how all people on earth live and work will profoundly change how all of us in livestock and protein production conduct our businesses and pursue our shared purpose – to sustainably and responsibly provide the world with a safe, nutritious, continuously available and affordable supply of animal-based protein. These conditions and drivers will inseparably be technology, customer experience and value-driven, and will fundamentally change how we do business with each other and our mutually served markets.

A 2014 report from Frost and Sullivan[2] looking out to 2025 identified 12 megatrends and 10 transformational shifts that are profoundly impacting how businesses will serve changing global societies and cultures. It is several of these same megatrends and transformational shifts that will impact (and are now already impacting) all livestock and protein production industries – in particular:

Megatrends and Transformational Shifts

- **Connectivity and Convergence** – There are two main aspects to connectivity – that which is technological and that which is strategic (and leads to convergence).
    - **Technological connectivity:** Humanity is rapidly approaching a time where everyone and everything will be connected everywhere all the time. The increasing speed and expanding bandwidth afforded by fibre-optic networks and 5G wireless networks will enable an entirely new level of within- and between-business connectivity, communication and data-handling capacity – particularly as the costs of these new technologies reduce over time. With the broad penetration of IoT-targeted low-cost LPWAN (low-power wide area network) technologies like NB-IoT, LTE-M, LoRa, SigFox and Weightless; sensor networks will become ubiquitous.
    - **Strategic connectivity:** Aided in part by advancements in technological connectivity, companies in unrelated industries are converging on new opportunity space to identify, explore, develop and synthesise multiple technologies and platforms. To capitalise on new opportunity space, companies from unrelated industries are forming strategic partnerships to leverage their respective core technologies by integrating them into something entirely new – interdependent business ecosystems.
- **New Business Models** – Increasing connectivity, mobility and digital platforms are resulting in entirely new business models. B2C (business to consumer), B2B (business to business) and C2C (consumer to consumer) online services have revolutionised our lives – we can work, travel, buy, sell, borrow, invest, bank, be entertained and communicate in ways never before possible. Subscription-based and transaction fee-based "as-a-service" business models will become the norm. New and secure electronic ways to instantly transfer money at minimal cost to anyone in the world and inexpensively and securely store money anywhere in the world will continue to replace more traditional payment methods and banking institutions.
- **Smart is the New Green** – Smart "sensorised" cities/buildings/homes are emerging, where inter-connecting existing systems with each other and connecting those systems to cloud-based platforms – in effect creating a system of systems – is enabling substantial improvements in efficiency, cost reduction and risk mitigation.
- **Health, Wellness and Wellbeing** – Advancements in information technology, digitalisation and miniaturisation are revolutionising healthcare. The speed and precision of diagnostics and monitoring is improving rapidly, and with it is improving the speed, precision, accuracy and confidence of decision-making. As the machine learning and artificial intelligence capabilities of these technologies advance, the information they generate will move from descriptive to predictive to prescriptive.

The above megatrends translate into several transformational shifts: connected living, wearable computing, sensorisation of things, smart cities and big data clouds. We are all becoming interconnected through what we carry, what we wear, where we sit, where we walk and what we ride in. The resulting data is continuously pouring into massive and growing data clouds where machine learning methods are continuously applied and generate algorithms that advise us, as well as predict and prescribe.

Coming to a Farm Near You

When it comes to agriculture, in many ways we really don't need to predict the future, we merely need to observe what is happening with humanity and businesses in more population-dense areas and regions around the world. The same megatrends and transformational shifts that

have been profoundly changing how much of the world does business and how most people on earth live is now also profoundly changing how we live and do business in livestock and protein production.

The same "everyone and everything connected everywhere all the time" dynamic that we are approaching globally for humanity in general will also become the norm in sparsely populated rural regions where virtually all crop and livestock production are located.[3] Just as is the case with smart cities; advancements in rural connectivity will lead rapidly to livestock businesses, farm sites, buildings, people and animals all becoming connected to each other and to cloud-based digital and analytic platforms. This, in turn, will enable smart barns, farms, production systems and production networks – with increasing adoption of available sensor, controller and communications technologies.

Traditional models based on marketing and selling of products, brands and bundles will disappear; transitioning to subscription-based and outcome-based revenue-sharing models built around "*as-a-service*" business ecosystems. Current product portfolios will be absorbed into these business ecosystems, becoming inextricably integrated with sensors and other hardware technologies – all inter-connected by firmware and software throughout.

The global livestock industries are moving further and faster to a much more communicative, coordinated, collaborative, connected and integrated structure. These changes will come much faster than we think possible, the magnitude of these changes will be much bigger than we now imagine, and many if not most of the major drivers of these changes will come from outside of livestock and protein production.

To effectively manage and support well-informed operational decision-making across the entire spectrum of intra-business (site, pod, flow, pyramid, division, system) and inter-business (area, region, network) levels necessitates an ecosystem of well-designed, standardised, integrated, widely adopted and broadly functional technologies and platforms for continuously generating, managing, synthesising, analysing and distilling enormous volumes of data into decision-ready information at both a local and global decision-making level. Adequate incentives for collaborating on the design & development, implementation & operation and ongoing support & participation in such an ecosystem must exist for it to be sustainable.

Overall, the livestock and protein production industries we all participate in will see emerge a vastly more functional way to manage data and information that operationally provides:

[1] micro-level "decision-ready" information that producers, veterinarians and allied industry can utilise to quickly make better informed operational decisions about the site/flow plans they are executing (e.g., rate of progress, reaching milestones, flagging site/flow-level problems that require execution of further investigation and any necessary corrective contingent actions)

[2] macro-level monitoring information that indicates if progress is being made at the business, regional and network levels and if larger, broader milestones are being met; as well as to identify areas within regions and/or branches within networks where the coordinated execution of corrective contingent actions across multiple sites/flows/systems may be warranted

[3] global-level monitoring and surveillance to detect and track global disease behaviour, livestock health threats and benchmark global health, welfare and performance

Further, our livestock and protein production industries will see emerge far better ways to leverage data and information beyond their core business uses – in both the research arena as well as for official programme and/or emergency uses. In effect, we will see a new animal health, welfare and productivity terrain embodied as interconnected ecosystems – a system of systems.

The Conceptual Framework

> *"Fools ignore complexity. Pragmatists suffer it. Some can avoid it. Geniuses remove it. You can't communicate complexity, only an awareness of it. Simplicity does not precede complexity, but follows it."*
>
> Alan Perlis[4]

A Dynamic Environment

The 'tectonic plates' that make up our food animal agricultural topography are shifting – a new 'terrain' is developing under our feet. In fact, in a foundational sense this shift has largely already happened. Most of the fundamentally important technologies and systems that will drive (and are driving) this transformation already exist – what we're lacking at this point in time is sufficient interconnection and deployment of those technologies and systems throughout our agricultural infrastructure. But that will change and is changing... and it will change faster than we believe possible.

In this new terrain, everything that can be connected will be connected. Everything that can be automated will be automated. Everything that can happen faster will happen faster. This will be driven by the broad adoption of already existing (and a continual pipeline of emerging) technologies that are produced and supported at an increasingly cost-effective level as adoption scales. The LPWAN wireless communication technologies scaling in the US (that are already becoming well established across Europe) specifically designed for IoT applications will provide more reliable and substantially lower cost connections for networks of devices and sensors. This will further (and faster) drive the adoption of cloud-based databases and, in turn, further (and faster) drive the real-time convergence and aggregation of data streams from more sources. This, in turn, will drive the leverage of these aggregate data through the application and leverage of the machine learning and artificial intelligence.

In this new terrain, everything that can be measured will be measured. Everything that can be analysed will be analysed. Every bit of information that can be leveraged will be leveraged. We will not only learn faster, we will learn things that were simply not possible to learn with our traditional analytic and learning methods – institutional-based research using classic time-bounded experimental methodologies, with the results inferred to apply to a continuous operational context. Instead, more (possibly even most) learning and knowledge of greatest operational value to livestock and protein producers will be generated directly

and relatively real-time from industry-scale commercial operations – commercial operations will become both research knowledge generator and consumer.

In this new terrain, anything that can be software will be software. Software algorithms will not only take raw data and in real-time generate decision-ready output values (that people then assimilate, synthesise, interpret and act on); the algorithms themselves will also be built to interpret, diagnose, recommend solutions with the highest probability of success and monitor the continuous response to solution implementation. As a result, the speed of decision-making will accelerate, and the role of people – farm personnel, production system management, veterinarians, suppliers, allied businesses – will change in some very profound ways.

Cyber-physical Systems

In 2006, Helen Gill, Program Director for Embedded and Hybrid Systems at the National Science Foundation in the United States, coined the term "cyber-physical systems" (CPS).[5] A cyber-physical system has been defined as:

"... engineered systems that are built from and depend upon, the seamless integration of computation and physical components."[6]

"... an orchestration of computers and physical systems. Embedded computers monitor and control physical processes, usually with feedback loops, where physical processes affect computations and vice versa."[7]

In effect, a cyber-physical system's purpose is to provide a broad digitalisation and comprehensive analysis of our physical reality on a continuous basis to support leveraging that analysis via better informed decision-making. The familiar (and overused) term "Internet of Things" is merely descriptive of the interconnected infrastructure necessary for that digitalisation to occur and be leveraged. The evidence of CPS can now be found touching virtually every aspect of our daily lives – CPS are becoming ubiquitous.

We use smartphones from the moment we wake up to the moment we fall asleep. There is not just an app for everything we can imagine, there are multiple apps for each of everything we can imagine... and apps for many things we had never before imagined. We have smart appliances and smart entertainment systems in our smart homes living in smart cities. We tell our interactive artificial intelligence devices what we want delivered to our homes, what music we want to hear, who we want to talk to and see, and what we want on our schedule – and they do our bidding. We ask these smart devices virtually anything we can think of and get the answers effectively immediately. We drive our smart (and getting smarter) cars, ride on smart (and getting smarter) trains and travel in smart (and getting smarter) planes to vacation at smart resorts while staying in smart hotels. And many, if not most (and eventually all) of these CPS are now or will soon become interconnected.

The same saturation of CPS has not (yet) permeated our world of agriculture. However, the unseen development and formation of the technological infrastructure has been building for some years now, with the more visible aspects of our new "Smart Farming" and "Precision Agriculture" terrain – the as-yet unfamiliar mountains and valleys, waterways and shorelines – is what more of us are now beginning to see take shape before our eyes.

Precision Agriculture / Precision Livestock

> *"A good tool is an invisible tool. By invisible, I mean that the tool does not intrude on your consciousness; you focus on the task, not the tool."*
>
> Mark Weiser[1]

The advent of Precision Agriculture/Precision Farming effectively began with the development of geographical information systems (GIS) in the 1960s/1970s and has advanced, organised and commercialised dramatically (and globally) since.[8,9,10,11,12,13,14] Focused primarily on crop production, Precision Agriculture has moved from being a leading-edge approach to crop farming to now rapidly becoming standard practice, effectively a cost-of-doing-business. Precision Livestock Farming (PLF) will follow the very same trajectory.

PLF and everything it incorporates (CPS, IoT, sensor networks, cloud computing, big data, artificial intelligence, machine learning) has been building for more than two decades.[15,16,17,18,19] And along with PLF are coming dramatic changes in diagnostics (characterising the microbiome, meta-genomics, nano-diagnostics, point-of-care diagnostics), devices (PLF-based detection & monitoring sensor systems, smart dosing systems...), digital platforms (integrated apps, web platforms, cloud databases) and data analytics (mining of massive datasets, machine learning, artificial intelligence...). These four aspects – diagnostics, devices, digital platforms and data analytics – we will refer to collectively as the "4Ds".

Diagnostics

Three major transformational shifts continue in the area of diagnostics:

1. Comprehensive granularity (whole genome sequencing, microbiome and metagenomics)
2. Holistic synthesis (diagnostic results integrated with contextual metadata)
3. Right here, right now (real-time point-of-care testing)

The complete genomic composition of infectious agents and individual animals can now be determined in granular detail, with the single biggest constraint to routine use of whole genome sequencing (WGS) being cost. However, as is the case with all new technologies with operational value potential, the cost of WGS will decrease over time and adoption will become mainstream. As whole-genome sequencing becomes commonplace and as the analytic methods of bioinformatics improve, we will increasingly be able to connect genomic composition to its phenomic expression and, as a result, learn how to more rapidly drive genetic improvement as well as better manage and mitigate the impacts of disease that constrain the realisation of genetic potential. Beyond complete sequencing of individual organisms, the comprehensive sequencing of the microbiome that exists in, on and around individual animals and the populations that they comprise will, with the use of improving bioinformatic methods and experience with their application and interpretation, provide a broader and deeper set of information and knowledge never before possible.

The integration of contextual metadata that characterise individual animal and population nutrition, environment, management and health will provide a much more holistic

(and realistic) understanding of the factors and cofactors influencing health, welfare and productivity. Access to real-time data originating from relevant measurements of nutrient composition, diet formulation, internal environment, external environment, management and health protocols (as well as compliance to those protocols) synthesised with diagnostic and monitoring results will provide decision-makers throughout all operational levels with decision-ready information. This will enable more timely and optimally effective intervention solutions to be crafted and applied with greater confidence of favourable outcomes.

Large, high-volume and sophisticated central diagnostic testing laboratories, supported by very well developed and rapid delivery infrastructure, will continue to be a key contributor to the health, welfare and productivity of livestock as well as the profitability of livestock businesses. Complementing these central laboratories, we are on the verge of the emergence and rapid growth of real-time on-farm/near-farm 'point-of-care' (PoC) diagnostic testing technologies. PoC devices and assays will be capable of providing real-time/near-real-time diagnostic results from samples tested at or near the site of collection (reducing the transport of infectious and high-risk samples) that can be acted on immediately with a high degree of confidence. These cloud-connected PoC technologies will be integrated in real time with relevant sensor-origin data, providing decision-makers with far better context for understanding their diagnostic results and taking action.

Devices

Much of the above-mentioned contextual metadata will originate from a range of implemented sensors continuously recording and processing data. Sensors inside of, attached to and surrounding animals will record a host of individual animal and cohort data, environmental data and operational process data to maximise performance and minimise cost. Sensors worn by, carried by and surrounding personnel will record a variety of activity and movement data useful for improving processes, process compliance and efficiency. Sensors attached to and integrated into operational equipment and assets will continuously transmit asset and equipment usage and performance data to maximise asset leverage and monitor critical control points to predict failure probabilities and enable preventive maintenance.

The aggregate of these sensors and their related algorithms will be continuously transmitting, processing, synthesising, interpreting, predicting, prescribing in real-time. A global explosion in the number of sensor technologies has been occurring across many industries for some years now, and we are seeing a rapidly increasing array of such technologies targeting use in livestock and protein production.

Digital Platforms

We interact with any number of digital platforms throughout every day. The platforms that engage us relate to our work, health, food, entertainment, education, shopping, communication, banking – virtually every aspect of our lives. These platforms inform us, educate us, improve our health and wellbeing, entertain us, connect us, supply us, save us time and money – make our lives better.

In livestock and protein production there is a growing surge of digital platforms (App-Cloud-Web Interface) accompanying the surge in diagnostic and device technology. These platforms will serve as digital 'connect-the-dots' hubs to which specific diagnostic and device technologies will connect to and integrate with – in effect, they will become central "go to" digital environments acting as a home-base, serving also as a "go through" conduit that enables users to seamlessly drill down to the specific connected technologies and return to the home-base just as seamlessly. These platforms will make us more informed, efficient and effective in the execution of our professional roles. They will better connect us and enable levels of communication and understanding far beyond what was possible a few short years ago.

Data Analytics

With the adoption and scaling of these new diagnostic, device and digital platform technologies comes their natural by-product – data, massive volumes of data continuously creating mountains and lakes and oceans and huge billowing cloud banks of data. Along with all of these immense masses of seemingly incoherent data comes tremendous opportunity – to process and arrange data, to synthesise and distill information, to create knowledge, to predict and prescribe.

Traditional descriptive and statistical methods of analysis can be useful to a degree, but require significant human resources with high analytic competencies to mine the data and find the leverageable knowledge nuggets. In many respects, our classic analytic methods and infrastructure are simply not sufficient to continuously mine and maximise the leverage of the aggregate data being continuously generated.

To meet the continuous needs of business and operational decision-makers, reliable information and actionable knowledge must be continuously real-time/near real-time – enter the analytic categories of machine learning (ML) and artificial intelligence (AI). Physicists, engineers and data scientists have effectively used ML/AI methods to mine massive datasets for many years – and these analytic methods will be just as useful adapted to mining the mountains and oceans of data continuously generated by the aggregate diagnostic, device and digital platform PLF technologies.

To Conclude...

Waves of innovation in the form of precision livestock technologies are coming to livestock and protein production. These technology waves will be comprised of any of four fundamental categories – diagnostics, devices, digital platforms and data analytics.

As is typical for all new things, the evaluation and adoption of each PLF technology that is offered to the livestock market will no doubt follow the dynamics of the classic model for diffusion of innovations first described by Everett Rogers in 1962.[20] The livestock producers who are innovators and early adopters that are the first to test and adopt valuable PLF technologies will benefit from their adoption as a competitive advantage. For the late adopters, adoption of successful PLF technologies will become a cost of doing business.

Not all PLF technologies will be successful – some of these PLF technologies that are developed will ultimately prove to be broadly valuable and become widely adopted, some will be proven to have value under limited conditions and will find a sustainable niche, and others will prove to be non-viable and will be abandoned. Ultimately, the determinant

of success for any PLF technology will be whether or not it serves an unmet need or better meets an existing need.

One thing is certain – the waves of precision livestock farming technologies are coming, and to fulfill our shared purpose of feeding the world as contributors to livestock and protein production we must be prepared to discover and embrace those which help us achieve that purpose.

"An innovation will get traction only if it helps people get something that they're already doing in their lives done better."

Clayton M. Christensen[21]

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