MACHINE-LEARNING-ENABLED TOOL CHANGER FOR MUSHROOM CROP MANAGEMENT SYSTEM

Abstract

A robotic mushroom crop manager periodically or continuously receives mushroom bed data corresponding to a mushroom bed including growing mushrooms at a plurality of times. A trained mushroom bed model is used to process the mushroom bed data to generate mushroom bed state vectors respectively characterizing corresponding states of the mushroom bed at the plurality of times. Crop management equipment is controlled to perform a crop management program comprising a sequence of actions to be performed by crop management equipment comprising, for each current action in the sequence of actions, selecting, based on corresponding a current mushroom bed state vector, a selected crop management tool from a plurality of crop management tools. The crop management equipment is controlled to use the selected crop management tool to perform the current action on the mushroom bed.

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Background/Summary

FIELD

[0001] The present disclosure relates generally to techniques for the cultivation and harvest of agricultural crops, and in particular for the automated cultivation and harvest of mushrooms.

BACKGROUND

[0002] In typical commercial mushroom growing operations, mushrooms are grown in growing beds on the surface of casing soil over substrate in a series of weekly intervals called flushes. Each flush is picked several times per day over a five-day period, and typically two to three flushes are harvested. The size at which the mushrooms are picked depends on market requirements.

[0003] European and North American commercial production of button mushrooms typically occurs on "Dutch Style" substrate filled shelves, using a two or three flush cropping cycle. The substrate is typically a composted mixture of wheat straw, animal manure, and gypsum. The substrate is pasteurized, inoculated, and colonized with spawn of a selected mushroom strain. The substrate is covered with a casing soil of peat and lime mixture in a layer approximately 45 to 50 mm deep, which is then ruffled with compost added to the casing to mix mushroom mycelium into the casing.

[0004] Traditionally, commercial mushroom farm operations rely on manual labour to harvest the mushrooms. Manual labour is costly, however, and difficult to optimize. Mushrooms typically grow at such a rate that the mushrooms approximately double in size every 24 hours. Using manual labour, each flush is picked only two or three times per day for the duration of the flush, meaning that a mushroom bed may become overgrown between pickings due to the growth rate of mushrooms, or that the growth of some mushrooms may be negatively impacted due to the build-up of CO_2 beneath the surface. In order to prevent overgrowth of a mushroom bed, a flush can be picked more frequently, but picking at a higher frequency is difficult and costly to accomplish with manual labour. When a bed becomes overgrown, the mushrooms may run out of room and grow into each other, thereby reducing yield, increasing stem growth, and/or causing deformation of each individual mushroom thereby adversely affecting the quality and value of the harvested mushrooms.

[0005] The automated mushroom harvesting apparatus and system by Bourdeau et al. disclosed in WIPO International Publication Number WO 2023/010198 A1 solves many of the challenges associated with the automated picking of cultivated mushrooms. The system includes a tool change and cleaning station comprising a tool rack having a plurality of slots for supporting a plurality of end effectors. The plurality of end effectors includes end effectors of different sizes for harvesting different sizes of mushrooms.

[0006] There remains, however, a need for improved techniques to optimize the total yield and overall effectiveness of automated mushroom cultivation and harvest systems which addresses at least some of the shortcomings of previous solutions and provides yet further advantages, thereby providing a material value over prior techniques.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] Embodiments will now be described, by way of example only, with reference to the attached Figures.

[0008] FIG. **1** is a block diagram of an automated mushroom crop management system.

[0009] FIG. **2** is a block diagram of a robotic mushroom crop manager.

[0010] FIG. **3** is a figurative drawing of a mushroom bed.

[0011] FIGS. **4** & **5** show perspective views of one non-limiting embodiment of crop management equipment.

[0012] FIG. **6** is an image of an actual mushroom bed with growing mushrooms in real growth medium.

[0013] FIG. **7** is an image of a synthetic mushroom bed with synthetic mushrooms.

[0014] FIG. **8** is a block diagram of a mushroom crop management tool coordinator.

[0015] FIG. **9** is a flowchart of a method performable by one or more of the robotic mushroom crop managers of FIG. **2** and/or the automated mushroom crop management system of FIG. **1**.

[0016] FIG. **10** is a flowchart of a method performable by the mushroom crop management tool coordinator of FIG. **8** and/or the automated mushroom crop management system of FIG. **1**.

[0017] It is to be understood that the accompanying drawings are used for illustrating the principles of the embodiments and exemplifications of the subject-matter discussed herein. Hence the drawings are illustrated for simplicity and clarity, and not necessarily drawn to scale and are not intended to be limiting in scope. Reference characters/numbers are used to depict the elements of the subject-matter discussed that are also shown in the drawings. The same corresponding reference characters/numbers are given to a corresponding component or components of the same or similar nature, which may be depicted in multiple drawings for clarity. In particular, specific embodiments or categories of embodiments of an element designated by a particular reference character may be distinguished by means of a suffix, wherein the specific embodiment designated by a reference character having a suffix is a species of the more general element having the same reference character lacking the suffix. For example, an element shown in the drawings and designated by the reference character ###n is a species of the more general element designated by reference character ###, and thus possesses all of the features of the more general element. Text may also be included in the drawings to further clarify certain principles or elements of the invention. It should be noted that features depicted by one drawing may be used in conjunction with or within other drawings or substitute features of other drawings. It should further be noted that common and well-understood elements for creating a commercially viable version of the embodiments discussed herein are often not depicted to facilitate a better view of the principles and elements of the subject-matter discussed herein. Throughout the drawings, sometimes only one or fewer than all of the instances of an element visible in the view are designated by a lead line and reference character, for the sake only of simplicity and to avoid clutter. It will be understood, however, that in such cases, in accordance with the corresponding description, that all other instances are likewise designated and encompassed by the corresponding description.

DESCRIPTION

[0018] Improved techniques for automated cultivation and harvest of mushrooms are disclosed herein. More particularly, improved techniques for automated selection of crop management tools by robotic mushroom crop managers are disclosed herein. The techniques include a robotic mushroom crop manager operative to generate a machine-learning-based model based on previous actions performed on a mushroom bed using tools selected from a plurality of tools, and to continuously or periodically train the model based on mushroom bed data collected while the robotic mushroom crop manager performs a crop management program. The techniques also include an automated crop management tool selection system including a plurality of like robotic mushroom crop managers communicatively coupled with a mushroom crop management tool

coordinator operative to generate a machine-learning-based model based on previous actions performed on a plurality of mushroom beds by the plurality of like robotic mushroom crop managers using tools selected from a like plurality of tools, and to continuously or periodically train the model based on mushroom bed data collected while the robotic mushroom crop managers perform respective crop management programs.

[0019] With reference to FIG. **1**, an automated mushroom crop management system **000** may have a plurality of robotic mushroom crop managers **100**A, **100**B . . . **100**N communicatively coupled with a mushroom crop management tool coordinator **700** via a network **900**.

[0020] Each robotic mushroom crop manager **100**A, **100**B . . . **100**N may be an individual instance of the robotic mushroom crop manager **100** shown in FIG. **2**. The robotic mushroom crop manager **100** may have a robotic mushroom crop manager controller **200**, and crop management equipment **300**. The robotic mushroom crop manager **100** may have or be operative to cooperate with a tool exchange plate **500** including a plurality of crop management tools **510**A, **510**B . . . **510**N. The robotic mushroom crop manager **100** and the tool exchange plate **500** may be, include, or be a similar to or a modification of, embodiments of a mushroom harvesting robot and tool change station, respectively, as described and shown in WIPO International Publication Number WO 2023/010198 A1, the entirety of which is incorporated herein by reference.

[0021] The robotic mushroom crop manager controller **200** may be operative to control the crop management equipment **300** to perform a crop management program. The robotic mushroom crop manager controller **200** may have a processor **210**, a memory **220**, a storage **230**, a communications interface **240**, and input/output equipment **250**. The memory **220** may store instructions operable by the processor **210** using the storage **230**, the communications interface **240**, and the input/output equipment **250** to performs the functions described herein. In particular, the memory **220** may store a crop management program engine **222** and a mushroom bed data collector **224**. The memory **220** may also store a mushroom bed data processor **226**. The robotic mushroom crop manager controller **200** may interface with the crop management equipment **300** in order to communicate with and to control the crop management equipment **300** as described herein.

[0022] The crop management equipment **300** may have at least one crop management device **310** and sensors **320**. The sensors **320** may include optical imagers **322** (intended to encompass either a single optimal imager or a plurality of optical imagers as required by context), and may also include other sensors **324** (likewise). The robotic mushroom crop manager controller **200** is operable to use the crop management program engine **222** to control the crop management equipment **300** to use the crop management device **310** to perform a crop management program **232**, which may be stored in the storage **230**. At the same time, the robotic mushroom crop manager controller **200** is operable to use the mushroom bed data collector **224** to use the sensors **320** to collect mushroom bed data, as described herein.

[0023] With reference to FIG. **3**, the processor **210** is operative to use the crop management program engine **222** to control the crop management equipment **300** to perform the crop management program **232** relative to a mushroom bed **400** containing a number of mushrooms **410** (only one of which is identified by a reference character and lead line to avoid clutter) in a growing medium **420**. The growing medium **420** may be of any suitable form or composition. For example, the growing medium **420** may include a casing soil, which may include a peat and lime mixture, layered atop a substrate, which may include a composted mixture of wheat straw, animal manure, and gypsum, which is pasteurized, inoculated, and colonized with spawn of a selected mushroom strain. The crop management program **232** may include a sequence of actions to be performed by the crop management equipment **300**, including actions to be performed by the crop management device **310**. Without limitation, such actions may include: moving the crop management equipment **300** to or above any location on the mushroom bed **400**; using the crop management device **310** to harvest a specific mushroom **410** at a particular location in the mushroom bed **400**; and using the crop management device **310** to move or otherwise disturb the growing medium **420** at a particular

location in the mushroom bed **400**.

[0024] In particular, the processor **210** may generate and operate a mushroom bed model **260** of the mushroom bed **400**, and to perform the crop management program **232** based at least partly on the mushroom bed model **260**. The crop management program engine **222** may further be operable, for a given one of the sequence of actions in the crop management program **232**, and for a given state of the mushroom bed **400** according to the mushroom bed model **260**, to select one of the crop management tools **510**A, **510**B . . . **510**N for performance of that action by the crop management device **310**.

[0025] One non-limiting embodiment of crop management equipment **300** is shown in FIGS. **4** & **5**. The crop management device **310** comprises a robotic arm **330** operatively mounted to a carriage assembly **340**. The robotic arm **330** comprises a shoulder **332**, an upper arm **334** pivotally mounted to the shoulder **332**, an elbow **336**, and a forearm **338** pivotally mounted to the upper arm **334** at the elbow **336**. An end effector **350** is releasably mounted to the free end **331** of forearm **338**.

[0026] The sensors **320** may be mounted to or proximal the crop management device **310** of the crop management equipment **300** so as to be operable to sense the mushroom bed **400** at or about the current position of the crop management device **310**. In particular, at least some of the optical imagers **322**, which may be digital cameras, may be coupled to the crop management equipment **300** adjacent or proximal the crop management device **310** in such a way as to provide a field of view containing the crop management device **310** and an area of the mushroom bed **400** in which the crop management device **310** is operable to harvest mushrooms **410** in the field of view. For example, one of the optimal imagers **322** may be a harvesting imager, covered by a transparent harvesting imager shield **323**, mounted at an underside **339** of the forearm **338**, which may be proximal the end effector **350** relative to the elbow **336**. In this way, a field of view of the harvesting imager, which may be a plan or overhead view, may coontain a portion of the mushroom bed **400** beneath the end effector **350** in use, and may also contain at least a portion of the end effector **350** itself. Another one of the optimal imagers **322** may be a trimming imager, covered by a transparent trimming imager shield **325**, mounted to the robotic arm **330** or the carriage assembly **340** and positioned, oriented, and configured in such a way as to provide an elevation, side, or perspective view of the portion of the end effector **350** and portion of the mushroom bed **400** beneath the end effector **350** when in use, which field of view may correspond to the field of view of the harvesting imager, in that they are directed to a common object viewed from different angles. For example, the trimming imager may be mounted at an underside of the **339** of the forearm **338**, but now proximal the elbow **336** relative to the end effector **350**, and aimed toward the end effector **350**. Alternatively, the trimming imager may be mounted at an underside of the upper arm **334**, the shoulder **332**, or to the carriage assembly **340**, and positioned, oriented, and configured to provide the field of view described herein.

[0027] As noted above, the sensors **320** may include other sensors **324**, which may or may not be limited by field of view in this way. The other sensors **324** may include one or more of an air temperature sensor, an air humidity sensor, a motion sensor, an orientation sensor, a light sensor, a soil pH sensor, a soil moisture sensor, a soil temperature sensor, a soil nutrient sensor, a soil pest/insect sensor, and a soil pollution sensor. Any one or more of the other sensors **324** may be positioned or mounted at the robotic arm **330**, which may also be at an underside of the robotic arm **330**

[0028] The mushroom bed data collector **224** may be operable by the processor **210** to collect using the sensors **320** a stream of data about the state and conditions of the mushroom bed **400** including the growing mushrooms **410** and optionally also the growing medium **420** (collectively, "mushroom bed data"). In particular, the mushroom bed data collector **224** may use the optical imagers **322** to collect a continuous stream of images of the mushroom bed **400** in the field of view of the optimal imagers **322**. The optical imagers **322** may be operated to continuously collect images as the crop management device **310** is continuously moved from position to position above

the mushroom bed **400** while performing the crop management program **232**. The mushroom bed data collector **224** may be further operable to collect using the other sensors **324**, when provided, a stream of data about the state and conditions of the mushroom bed **400** corresponding to the nature of such other sensors **324**.

[0029] In particular, the mushroom bed data may include, quantify, or enable determination of one or more properties or characteristics of the mushroom bed **400**, the growing mushrooms **410**, and optionally the growing medium **420**. A non-limiting list of such properties or characteristics of the mushrooms **410** may include: size; shape; density; defects; marks; quality grade; anomalies; surface texture; underside spacing between cap and growing medium; stem length; and stem orientation. When included, a non-limiting list of the properties or characteristics of the growing medium **420** may include: pH, moisture, temperature, nutrient quantities, pest/insect quantities, and pollution quantities. The mushroom bed data may be position-aware, in that it is associated with (which may be in the form of metadata) a collection location on the mushroom bed **400** where the mushroom bed data was collected by the sensors **320**. For example, the mushroom bed data may be indexed according to a virtual partitioning of the mushroom bed **400**. For example, as shown in FIG. **3**, the mushroom bed **400** may be divided by a set of gridlines **430** into a set of mushroom bed cells **440**, sometimes called 'sliding windows', and the mushroom bed data may be collected and indexed in accordance with the mushroom bed cells **440**. Such mushroom bed cells **440** may have any appropriate size, shape, or dimensions. In some embodiments, the mushroom bed cells **440** are squares having a side dimension of from about 0.5″ to about 5″, or at least about 1″, or about 1″, although other dimensions are possible and contemplated. Any suitable alternative arrangement may be used, including for example, a hexagonal tiling arrangement. The mushroom bed data may also be time-aware, in that it is associated with (which may be in the form of metadata) a collection time at which the mushroom bed data was collected by the sensors **320**. For example, when the mushroom bed data is or includes images of the mushroom bed **400**, the images may be indexed, labelled, or otherwise associated with a location on the mushroom bed **400** where the image was collected by the optimal imagers **322**, and may also be indexed, labelled, or otherwise associated with a time at which the image was collected by the optimal imagers **322**. The position and/or the time may be generated by the crop management equipment **300** itself and received by the robotic mushroom crop manager controller **200**, or it may be generated by the robotic mushroom crop manager controller **200**.

[0030] The sensors **320** may be operable to collect mushroom bed data in any desired time interval. For example, the sensors **320** may be operated to collect mushroom bed data every 1-1000 ms, although other time intervals are contemplated. The mushroom bed data collector **224** may receive raw mushroom bed data from sensors **320** using any communicative connection between the robotic mushroom crop manager controller **200** and the crop management equipment **300**. The connection may be a wired connection, a wireless connection, and may use the communications interface **240** to receive the raw mushroom bed data. The raw mushroom bed data may then be stored in the storage **230**. The processor **210** may operate the mushroom bed data processor **226** as part of a computer vision system to process the raw mushroom bed data into pre-processed mushroom bed data, which may also be stored in the storage **230**. For example, the mushroom bed data processor **226** may be operable to process images collected by the optical imagers **322** to augment, enhance, colour-correct, convert, or compress such images, or to identify, parameterize, or otherwise any of the properties and characteristics described above.

[0031] The processor **210** may also be operable to train and operate a mushroom bed model **260** of the mushroom bed **400** based on the mushroom bed data. In particular, the transformed mushroom bed data generated by the mushroom bed data processor **226** may include mushroom bed data vectors configured for ingestion by the mushroom bed model **260**. The mushroom bed data vectors may include or enable determination of any quantifiable properties or characteristics of the mushroom bed **400**, mushrooms **410**, and optionally the growing medium **420**, as described herein.

When the mushroom bed data is or includes a stream of images, including position-indexed and time-indexed images, as described herein, the mushroom bed data vectors may be or include the images in any suitable encoding, which may include or be labelled by, which may be by metadata, corresponding locations and times. Any suitable object-detection techniques or metrics may be used, which may include intersection-over-union similarity measures. For example, one non-limiting mushroom bed data vector includes any combination of at least some, or all, of the following attributes: time stamp; mushroom bed cell index (e.g. row and column indices); window size; light configuration (e.g. RGB values); distance/depth (which may be in combination with light configuration as RGB-D values); motion quantities (which may be speed, velocity, inertia values of camera, sensors, or related structure); environmental data (such as moisture, temperature, surface substrate quality; substrate grade); and metrics of mushrooms in window (such as size, density, number of high density clumps, proportion of high quality mushrooms). Other quantities and measures are possible and contemplated.

[0032] As discussed above, the mushroom bed data may enable a determination of properties or characteristics of the mushrooms **410** including without limitation: size; shape; density; defects; marks; quality grade; anomalies; surface texture underside spacing between cap and growing medium; stem length; and stem orientation. When the collected mushroom bed data is or includes a stream of images, as described herein, the mushroom bed model **260** may be trained to generate and predict such properties or characteristics, as described further below.

[0033] Specifically, the processor **210** may be operable to train the mushroom bed model **260** by using a comparer **280**. In an initial training stage, the mushroom bed data processor **226** may be used to generate mushroom bed data vectors based on mushroom bed data received as described herein, where the corresponding known mushroom bed state vectors encoding the properties and characteristics of the mushroom bed **400**, including the mushrooms **410**, and optionally the growth medium **420** are determined by an additional procedure.

[0034] For example, with reference to FIG. **6**, the mushroom bed **400** may be an actual mushroom bed **400** with live, growing mushrooms **410** in a real growth medium **420**, and the known mushroom bed state vectors encoding the properties and characteristics of the mushroom bed **400** may be determined manually, which may be by manual inspection. Alternatively, and with reference to FIG. **7**, the mushroom bed **400** may a synthetic mushroom bed **400″**, with synthetic mushrooms **410″**, and optionally synthetic growth medium **420″**, fabricated purposefully to possess preconfigured mushroom bed state vectors encoding a predetermined variety of the mushroom bed (including mushroom) properties and characteristics. In any case, the mushroom bed data vectors so received and generated may include or be labelled with the known mushroom bed state vectors. The mushroom bed model **260** may then process such labelled mushroom bed data vectors using the comparer **280** to determine differences between the known mushroom bed state vectors and the predicted mushroom bed state vectors generated by the mushroom bed model **260** based on the received mushroom bed data vectors, to learn to predict the corresponding known mushroom bed state vectors, and thus the known mushroom bed state.

[0035] The processor **210** may be operable to train the mushroom bed model **260** using any suitable techniques known in the art. A network architecture or topology may be established, and layers may be added which are associated with respective optimization functions, activation functions, and/or loss functions. One or more artificial neural networks may be used, and each may of any suitable type, including without limitation convolutional neural networks, recurrent neural networks, and deep learning neural networks. The mushroom bed model **260** may involve one artificial neural networks, or may involve multiple different artificial neural networks. The mushroom bed model **260** may include instructions using supervised or unsupervised machine learning, involving identifying and recognizing patterns in the mushroom bed data (in the form of the mushroom bed data vectors) to enable recognition of mushroom bed states of the mushroom bed. The mushroom bed data and the differences between the actual and predicted mushroom bed

state described herein which may be used to train the artificial neural network may be encoded in any suitable manner, such as, without limitation, an N-dimensional tensor, a matrix, or an array. Training of the artificial neural network may involve parameters initialized to random values, which are changed with each iteration, using any appropriate algorithm to converge to predetermined values. Such algorithms may include, for example, gradient descent, stochastic gradient descent (SGD), minibatch SGD, nonlinear conjugate gradient, limited-memory Broyden-Fletcher-Goldfarb-Shanno (L-BFGS), or Levenberg-Marquardt (LMA) algorithms. Training of the artificial neural network may employ any appropriate statistical model, which may be a multinomial logistic regression model, a random forest model, a decision tree, a logistic regression model, or a gradient boosting model.

[0036] As indicated above, the robotic mushroom crop manager **100** may also have or be operative to cooperate with a tool exchange plate **500**. In the embodiment shown in FIGS. **4** & **5**, the tool exchange plate **500** forms a part of the crop management equipment **300**, and is mounted to the carriage assembly **340**. The tool exchange plate **500** supports a plurality of crop management tools **510** (only one of which is identified with a reference character and lead line in order to avoid clutter). The crop management tools **510** are sized, shaped, and configured for coupling with and use by the robotic arm **330** end effector **350** to perform corresponding actions described herein. For example, different crop management tools **510** may have different sizes or configurations suitable for the harvesting of different sizes and/or types of mushrooms. Different crop management tools **510** may include, without limitation: suction cups with any suitable diameters, depths, dimensions, or configurations to accommodate any corresponding size, shape, or type of mushroom; grabbers with any number of fingers, such as 3, 4, 5, or 6, which may have knuckles or elbows; pipe-like tools with sharp, razor-like end to encircle a mushroom, which may be a mushroom pin, pass beyond it, and twist or otherwise disturb the substrate around it, in a circular manner; pipe-like tools with a moving section to close under a mushroom, which may be a mushroom pin, to lift it for transplantation, which may be in a circular manner; pipe-like tools with an end flattened to press on a mushroom, which may be a mushroom pin, to be destroyed but left in place to rot; irrigation tools; fertilization tools; spoon-like tools for substrate movement, manipulation, or transplantation; and tools with one or more environmental sensors embedded for real-time probing. Other types and arrangements of tools are possible and contemplated.

[0037] In particular, for each of the actions performable by the crop management device **310** relative to the mushroom bed **400** in accordance with the crop management program **232**, a crop management device **310** may employ a crop management tool **510** selected from a plurality of crop management tools **510**A, **510**B . . . **510**N. In particular, for a given set of conditions of the mushroom bed **400**, a particular crop management tool **510** may be optimally functional for the performance of the action required by the crop management program. For example, different crop management tools **510** may have different sizes, shapes, or configurations suitable for the harvesting of different sizes and/or types of mushrooms **410**. Different crop management tools **510** may have different sizes or configurations suitable for the movement or disturbance of the growing medium **420** at a particular location in the mushroom bed **400**. The foregoing are non-limiting examples. As such, optimal performance of the crop management program **232** may involve for at least some of the actions performed in accordance with the crop management program **232** a selection of a particular crop management tool **510** from the plurality of crop management tools **510**A, **510**B . . . **510**N which is optimal for the performance of that action given the corresponding conditions of the mushroom bed **400**.

[0038] For this purpose, the crop management program engine **222** may be operable by the processor **210** for selecting a crop management tool **510** from the plurality of crop management tools **510**A, **510**B . . . **510**N based on mushroom bed data collected from the mushroom bed **400**. In particular, the processor **210** may be operable to continuously or periodically train a tool selection model **270** based on the mushroom bed data of the mushroom bed **400** including at least the

mushrooms **410**, and optionally the growing medium **420**, which may be based on mushroom bed state vectors generated by the mushroom bed model **260**. The processor **210** may be operable to train the tool selection model **270** to select a specified crop management tool **510** selected from the plurality of crop management tools **510**A, **510**B . . . **510**N to perform a specified action on the mushroom bed **400** in order to produce a corresponding change in state of the mushroom bed **400**. The change in state of the mushroom bed **400** may include a change in state of mushrooms **410** and optionally growing medium **420** at a specified future time. Any appropriate future time may be specified, and may be from 1 second to 1 hour (3600 seconds). More distant future times are also contemplated. With respect to each such selection and corresponding action, the processor **210** may be operable to train the tool selection model **270** based on feedback regarding a desired change in state of the mushroom bed **400**, as further described below.

[0039] In particular, the processor **210** may be operable to train the tool selection model **270** by using an outcome optimizer **282**. As discussed above, the crop management program engine **222** may be operable to control the crop management equipment **300** according to a crop management program **232**, and the crop management program **232** may include a sequence of actions to be performed by the crop management device **310**. Without limitation, such actions may include: harvesting a specific mushroom **410** at a particular location in the mushroom bed **400**; and moving or otherwise disturbing the growing medium **420** at a particular location in the mushroom bed **400**. Each such action may be characterized by parameters defining a desired or optimal outcome. For example, where the action is harvesting a mushroom **410**, the desired or optimal outcome may include one or more of: minimizing damage to the mushroom **410**; minimizing time required to harvest the mushroom; minimizing damage to adjacent or surrounding mushrooms **410**; or minimizing disturbance of adjacent or surrounding growing medium **420**. With respect to such actions, each one of the plurality of crop management tools **510**A, **510**B . . . **510**N may produce a different actual outcome based on different properties of the particular crop management tool **510**, and different properties of the mushroom bed **400**, such as different sizes and/or types of mushrooms **410**, or different kinds or conditions of growing medium **420**. Given such different properties of the mushroom bed **400**, one of the plurality of crop management tools **510**A, **510**B . . . . **510**N when used to perform the required action may produce an actual outcome which is closer to a desired or optimal outcome than the other ones of the crop management tools **510**A, **510**B . . . **510**N. Therefore, for any given current state of the mushroom bed **400** (such as, a given current state of a particular mushroom **410**) and a given action to be performed on the mushroom bed **400** in accordance with the crop management program (such as, to harvest the mushroom **410**), the processor **210** may be operable to train the tool selection model **270** to predict which one of the plurality of crop management tools **510**A, **510**B . . . **510**N is likely to produce an actual outcome which is closer to the desired or optimal outcome of the action as compared to the other ones of the crop management tools **510**A, **510**B . . . **510**N.

[0040] In particular, and as discussed above, during performance of the crop management program **232**, the mushroom bed data collector **224** may be operable to use the sensors **320** of the crop management equipment **300** to periodically or continuously collect mushroom bed data from the mushroom bed **400**. In particular, the optical imagers **322** may be operable to collect a stream of images of the mushroom bed **400** in the respective fields of view of the optimal imagers **322** as the crop management device **310** is operated to perform actions on the mushroom bed **400**. More particularly, the mushroom bed data collector **224** may be operable to use the sensors **320** of the crop management equipment **300** to collect mushroom bed data from the mushroom bed **400** at a time before the performance of a given action on the mushroom bed **400**, and then also at a post-action time after the performance of the action on the mushroom bed **400**. In this way, when the crop management program engine **222** controls the crop management equipment **300**, and in particular the crop management device **310** to select a crop management tool **510** from a plurality of crop management tools **510**A, **510**B . . . **510**N, and to use the selected crop management tool

510 to perform a corresponding action on the mushroom bed **400**, the mushroom bed data collector **224** may be operable to use the sensors **320** of the crop management equipment **300** to collect mushroom bed data from the mushroom bed **400** at the pre-action time before the performance of the action and then also at the post-action time after the performance of the action on the mushroom bed **400**. The processor **210**, using the mushroom bed data collector **224**, may then be operable to determine an actual outcome of the performance of the action on the mushroom bed **400** using the selected crop management tool **510** based on differences between the pre-action mushroom bed state, which may in the form of mushroom bed state vectors generated by the mushroom bed model **260**, at the pre-action time and the post-action mushroom bed state, which again may in the form of mushroom bed state vectors generated by the mushroom bed model **260**, at the post-action time, and to determine an outcome difference, which may be by using the comparer **280**, between the actual outcome and a desired outcome in accordance with the crop management program **232**.

[0041] In particular, the processor **210** may use the outcome optimizer **282** to compare the actual outcome and the desired outcome of the action performed on the mushroom bed **400** using the crop management tool **510** selected from the plurality of crop management tools **510**A, **510**B . . . **510**N. The comparer **280** may receive from the mushroom bed model **260** a post-action mushroom bed state vector of the mushroom bed based on mushroom bed data collected at the post-action time after performance of the action by the selected crop management tool **510**, which encodes characteristics and properties of the mushroom bed **400** at the post-action time, and further receive from the mushroom bed model **260** a pre-action mushroom bed state vector of the mushroom bed based on mushroom bed data collected at the pre-action time before performance of the action by the selected crop management tool **510**, which encodes characteristics and properties of the mushroom bed **400** at the pre-action time, and the pre-action mushroom bed state vector and the post-action state vector to determine the actual outcome of the action. The processor **210** may then use the outcome optimizer **282** to compare the actual outcome of the action so generated with a desired outcome based on desired properties and characteristics of the mushroom bed **400** in accordance with the crop management program. As discussed above, a non-limiting list of properties or characteristics of mushrooms **410** includes: size; shape; density; defects; marks; quality grade; anomalies; surface texture underside spacing between cap and growing medium; stem length; and stem orientation. And, when included, a non-limiting list of the properties or characteristics of the growing medium **420** includes: soil pH, soil moisture, presence and/or concentration of gases (such as CO_2), soil temperature, soil nutrient, soil pest/insect, and soil pollution. Thus, the crop management program may include a desired outcome relative to any one or more of such properties and characteristics of the mushroom bed **400** to be caused by the performance of the action by the crop management device **310**, and the processor **210** may be operable to use the outcome optimizer **282** to compare and determine differences between the actual outcome with respect to such one or more properties and characteristics with the desired outcome of the action.

[0042] For example, where the action is harvesting a mushroom **410**, the desired or optimal outcome may include one or more of: minimizing damage to the mushroom **410**; minimizing time required to harvest the mushroom; minimizing damage to adjacent or surrounding mushrooms **410**; or minimizing disturbance of adjacent or surrounding growing medium **420**. The processor **210**, using the comparer **280** and the outcome optimizer **282**, may then use these differences to train the tool selection model **270** to learn to predict the actual outcomes of the performance of corresponding actions on the mushroom bed **400** using each of the plurality of crop management tools **510**A, **510**B . . . **510**N, and in this way to predict for a given action in the crop management program which one of the plurality of crop management tools **510**A, **510**B . . . **510**N is likely to produce an actual outcome which is closest to the desired outcome—that is, which is an optimal outcome.

[0043] For any given action performed using a selected crop management tool **510**, a time interval between the performance of the action and collection of mushroom bed data to determine an actual mushroom bed state as described may be any desired time interval. For example, the time interval may be about 0.1 to about 600 seconds, or about 1 to about 60 seconds, or about 5 to about 10 seconds, although other time intervals are contemplated. In order to use the comparer **280** and outcome optimizer **282** to compare and determine differences between the actual outcome with respect to one or more properties and characteristics of the mushroom bed **400** with the desired outcome of the action, as described above, the processor **210** may, for a given action, be operable to store tool selection data in a pending data structure **236**, which may be stored in the storage **230**, which associates the mushroom bed state at the time of the action, the time of the action, and the selected crop management tool **510** used to perform the action. Then, at or about an end of the time interval, the processor **210** may be operable to fetch the tool selection data from the pending data structure **236** for use by the comparer **280** and the outcome optimizer **282** to compare and determine differences between the actual outcome with respect to one or more properties and characteristics of the mushroom bed **400** with the desired outcome of the action, as described.

[0044] For example, where the action performed by one of the plurality of crop management tools **510**A, **510**B . . . **510**N is to harvest a specific mushroom **410**, the desired or optimal outcome may include minimizing damage to the mushroom **410**. The crop management program engine **222** may be operable to select one of the plurality of crop management tools **510**A, **510**B . . . **510**N to perform the harvesting action. The mushroom bed data collector **224** may be operable to control the crop management equipment **300** sensors **320**, and particularly the optical imagers **322**—including particularly the g imager and the trimming imager described above—to periodically or continuously collect images of the mushroom **410** before, during, and after harvesting of the mushroom **410** by the selected crop management tool **510**. For example, the mushroom bed data collector **224** may collect images of the mushroom **410** as it is lifted by the selected crop management tool **510**, as the mushroom **410** stem is trimmed, as the trimmed mushroom **410** is carried to a collection box, as the mushroom **410** is dropped in the collection box, and when the mushroom **410** is resting in the collection box. In particular, the harvesting imager may provide a plan or overhead view of the mushroom **410** immediately before it is grasped and lifted by the selected crop management tool **510** and after it is dropped in the collection box, while the trimming imager, which provides an elevation, side, or perspective view of the portion of the end effector **350** as described above, may provide a view of the mushroom **410** once it has been grasped and lifted by the selected crop management tool **510** and while it is being moved to the collection box. In this way, the collection of images with respect to the interaction between the selected crop management tool **510** and the mushroom **410** may be comprehensive.

[0045] Thus, the processor **210** of the robotic mushroom crop manager controller **200** may be operable, based on the mushroom bed data so collected, to use the mushroom bed model **260** to model and characterize the mushroom **410** at selected points, periodically, or throughout the harvesting action as described, and then to use the comparer **280** and outcome optimizer **282** to compare and determine differences between the actual outcome of the mushroom **410** with respect to one or more properties and characteristics with the desired outcome of the harvesting action, as described. This may include, for example, an amount or degree of damage caused to the mushroom **410**, which may be either to its cap or stem. The determined differences between the actual outcome with the desired outcome may then be used to further train the tool section model **270**.

[0046] The processor **210** may be operable to train the tool selection model **270** using any suitable techniques known in the art. A network architecture or topology may be established, and layers may be added which are associated with respective optimization functions, activation functions, and/or loss functions. One or more artificial neural networks may be used, and each may of any suitable type, including without limitation convolutional neural networks, recurrent neural networks, and deep learning neural networks. The tool selection model **270** may involve one or

more of the same artificial neural networks, or may involve different artificial neural networks. The tool selection model **270** may include instructions using supervised or unsupervised machine learning, involving identifying and recognizing patterns in the mushroom bed data (in the form of the mushroom bed data vectors) to enable recognition of mushroom bed states of the mushroom bed, and to enable prediction of a selected crop management tool to produce an optimal actual outcome. The mushroom bed data, used to generate mushroom bed state vectors as described, and the differences between the actual and desired outcomes described herein which may be used to train the artificial neural network may be encoded in any suitable manner, such as, without limitation, an N-dimensional tensor, a matrix, or an array. Training may be performed in any suitable manner, and may include iterative training using labeled training data as described herein. Training of the artificial neural network may involve parameters initialized to random values, which are changed with each iteration, using any appropriate algorithm to converge to predetermined values. Such algorithms may include, for example, gradient descent, stochastic gradient descent (SGD), minibatch SGD, nonlinear conjugate gradient, limited-memory Broyden-Fletcher-Goldfarb-Shanno (L-BFGS), or Levenberg-Marquardt (LMA) algorithms. Training of the artificial neural network may employ any appropriate statistical model, which may be a multinomial logistic regression model, a random forest model, a decision tree, a logistic regression model, or a gradient boosting model.

[0047] In order to optimize the speed and efficiency of selection of an optimal crop management tool **510** from the plurality of crop management tools **510**A, **510**B . . . **510**N given a required action of the crop management program, the processor **210** may be further operable to use a selection library manager **284**. As described above, the processor **210** may be operable to use the comparer **280** and outcome optimizer **282** to compare and determine differences between the actual outcome of a given action performed using a selected crop management tool **510** with respect to one or more properties and characteristics with the desired outcome of the action. At a certain point, the likelihood that a given crop management tool **510** may produce an optimal outcome as compared to the other ones of the plurality of crop management tools **510**A, **510**B . . . **510**N is sufficiently great that, thereafter, for a given action, when the relevant properties and characteristics of the mushroom bed **400** fall within respective preconfigured ranges the selection of that crop management tool **510** may also be preconfigured, such that use of the tool selection model **270** to determine a selected crop management tool **510** may be avoided.

[0048] To this end, the processor **210** may operate the selection library manager **284** to store in a selection library datastore **234**, stored in the storage **230**, predetermined tool selection data, which may be a record in a look-up table, associating a predetermined optimal one of the plurality of crop management tools **510**A, **510**B . . . **510**N with a given action included in the crop management program and a preconfigured combination of preconfigured ranges of the the properties and characteristics of the mushroom bed **400**. The selection library manager **284** may be configured to do so when a likelihood that a given crop management tool **510** may produce an optimal outcome as compared to the other ones of the plurality of crop management tools **510**A, **510**B . . . **510**N exceeds a predefined threshold. In some embodiments, the selection library manager **284** is configured to do so on any given successful action, that is when the determined differences between the actual outcome of a given action performed using a selected crop management tool **510** with respect to one or more properties and characteristics with the desired outcome of the action, as described above, matches within a predefined threshold. In other words, the selection library manager **284** may be configured to store in the selection library datastore **234** predetermined tool selection data on the very first instance of a successful action according to the noted predefined threshold.

[0049] Then, in general, as the processor **210** uses the crop management program engine **222** to perform the crop management program **232**, for each action performable in accordance therewith, the processor **210** may use the selection library manager **284** to determine when an optimal tool

selection threshold is met for a given one of the plurality of crop management tools **510**A, **510**B . . . **510**N in association with a given action in the crop management program and given preconfigured ranges of the properties and characteristics of the mushroom bed **400**, which may be preconfigured ranges of dimensions of a current mushroom bed state vector. For example, the given action may be harvesting a selected mushroom **410**, and the characteristics of the mushroom bed **400** may include one or more of: a size, shape, and orientation of the mushroom, including an orientation of the stem and spacing between an underside of the cap and top surface of the growing medium; and number, sizes, spacing, and orientations of surrounding mushrooms. The processor **210**, before using the tool selection model **270** as described above to select one of the plurality of crop management tools **510**A, **510**B . . . **510**N to perform the given action based on a current mushroom bed state, may first instead use the selection library manager **284** to access the selection library datastore **234** to determine whether the selection library datastore **234** contains predetermined tool selection data, which may be a record, encoding the above-described association—that is, for the given action, defines preconfigured ranges of the properties and characteristics of the mushroom bed **400** into which the current mushroom bed state falls. In this way, the processor **210** may avoid using the tool selection model **270** to select a crop management tool **510**, and instead select the crop management tool **510** identified in the predetermined tool selection data. The selection library manager **284** may operate in this way using less time and fewer computational resources than the tool selection model **270**, and in this way the overall performance of the crop management program by the crop management program engine **222** may likewise use less time and fewer computational resources.

[0050] The processor **210** may further operate the selection library manager **284** to update the selection library datastore **234**, stored in the storage **230**, as the crop management program **232** is performed. In particular, if and when a given action in the crop management program and given ranges of the properties and characteristics of the mushroom bed **400** is performed using one of the plurality of crop management tools **510**A, **510**B . . . **510**N based the selection library datastore **234** containing a record with matching predetermined tool selection data, as described above, but the action does not in fact produce an actual outcome within the preconfigured similarity with the desired outcome, as described above, then the processor **210** may be operable to use the selection library manager **284** to access the selection library datastore **234** to remove that record.

[0051] Thus, a robotic mushroom crop manager **100** as shown and described above is thus operable to optimize tool selection for use by harvesting equipment to perform actions of a crop management program on a mushroom bed. For example, the robotic mushroom crop manager **100** is operable to optimize selection of a crop management tool from a plurality of crop management tools available on a tool exchange plate for harvesting mushrooms from the mushroom bed, so as to minimize damage caused to the mushrooms and also to optimize time spent harvesting the mushroom. The robotic mushroom crop manager **100** is operable to train a tool selection model **270** based on collected mushroom bed data. A selection library manager **284** is operable, for a given crop management program action and mushroom bed state, to determine an optimal crop management tool by lookup in a selection library datastore **234**. In this way, the robotic mushroom crop manager **100** may be progressively configured for optimal crop management tool selection over time.

[0052] In order to accelerate and optimize the process of crop management tool selection by a particular robotic mushroom crop manager **100**, however, a plurality of like or similar robotic mushroom crop manager **100** may cooperate in such a way as to share, in effect, the lessons learned with respect to crop management tool selections made by all of them, so that any one of the robotic mushroom crop manager **100** may, in a given situation, benefit from the experiences of all of the others.

[0053] For this purpose, and as shown in FIG. **1** and as described above, the automated mushroom crop management system **000** may have a plurality of robotic mushroom crop managers **100**A, **100**B . . . **100**N communicatively coupled via a network **900**. Each one of the plurality of robotic

mushroom crop managers **100**A, **100**B . . . **100**N may be configured as described above, and in particular may be configured to develop its respective selection library **234** based on successful actions performed by its crop management equipment **300** using a selected one of the plurality of crop management tools **510**A, **510**B . . . **510**N as described above. The automated mushroom crop management system **000** may be configured such that one or more, which may be each, of the plurality of robotic mushroom crop managers **100**A, **100**B . . . **100**N is operable to benefit from the experience gained from all of them with respect to the selection of an optimal crop management tool **510** for the performance of a given action.

[0054] Specifically, one or more, which may be each, or which may be very one, of the robotic mushroom crop managers **100**A, **100**B . . . **100**N may store in its respective storage **230** a robotic mushroom crop manager (RMCM) list datastore **237** which stores records corresponding respectively to one or more of the other robotic mushroom crop managers **100**A, **100**B . . . **100**N. Each such record may store, among other things, an identifier and a communication address, which may be a network address, of the corresponding robotic mushroom crop manager **100**. Records corresponding to all or a subset of the other robotic mushroom crop managers **100**A, **100**B . . . **100**N may be stored in this way. In particular, for a given one of the robotic mushroom crop managers **100**A, **100**B . . . **100**N, records corresponding to only a subset of the other robotic mushroom crop managers **100**A, **100**B . . . **100**N may be stored, based on a similarity of respective parameters of the subset of other robotic mushroom crop managers **100**A, **100**B . . . **100**N and the given one of the robotic mushroom crop managers **100**A, **100**B . . . **100**N. Such parameters may include, without limitation: location of the other robotic mushroom crop manager **100**; and type or types of mushrooms **410** of the mushroom bed **400** associated with that other robotic mushroom crop manager **100**.

[0055] Thus, and as described above, when the processor **210** uses the crop management program engine **222** to perform the crop management program **232**, and uses the selection library manager **284** to access the selection library datastore **234** to determine whether the selection library datastore **234** contains predetermined tool selection data for the given action, and when it determines that the selection library datastore **234** does not contain predetermined tool selection data for the given action, the processor **210** may then be operable, which may be by use of the selection library manager **284**, the access the RMCM list **237** to determine whether it contains a record of other robotic mushroom crop managers **100**A, **100**B . . . **100**N having respective parameters similar within a predefined threshold to parameters of the robotic mushroom crop manager **100**. For example, the predefined threshold may be that a respective location of the other robotic mushroom crop manager **100** is within a predefined distance of a location of the robotic mushroom crop manager **100**, within a predefined distance of a location of certain crop management equipment **300**, and/or a type of the mushrooms **410** of the mushroom bed **400** associated with that other robotic mushroom crop manager **100** is the same or similar within a predefined threshold to those of the robotic mushroom crop manager **100**. In such case, the processor **210** may be operable, which may be using the selection library manager **284**, to generate a tool selection request message, which may encode in association the given action in the crop management program **232** and a current mushroom bed state vector, and to use the communications interface **240** to communicate, which may be via the network **900**, to those other robotic mushroom crop managers **100** whose parameters are the same or similar within the predefined threshold. The processor **210** may be configured either to wait up to a preconfigured waiting time for a reply before continuing to perform the crop management program **232**, or it may be configured to skip the action involved, and may further be configured to reschedule the action to a later point in the crop management program, which may be done either immediately or after the preconfigured waiting time. For each of the other robotic mushroom crop managers **100** to which the tool selection request message was sent, and respectively throughout, the processor **210** thereof may be operable to use the communication interface **240** to receive the tool selection request message, and may further be

operable, which may be using the selection library manager **284**, to access the selection library datastore **234** to determine whether it stores predetermined tool selection data which matches the given action and the mushroom bed state vector encoded in the tool selection request message, which may be in the same manner as is done by the sending robotic mushroom crop manager **100** with respect to its own selection library datastore **234** as described above. In the case that the selection library datastore **234** does indeed store such predetermined tool selection data, then the processor **210** of the corresponding other robotic mushroom crop manager **100** may be operable, which may be using the corresponding selection library manager **284**, to generate a tool selection reply message encoding the optimal tool selection encoded in that predetermined tool selection data, and may further be operable to use the corresponding communications interface **240** to transmit the tool selection reply message to the original robotic mushroom crop manager **100** which had sent the tool selection request message. The processor **210** of that original robotic mushroom crop manager **100** may then be operable using the corresponding communications interface **240** to receive the tool selection reply message. Then, the processor **210** may be operable using the selection library manager **284** to store in the selection library datastore **234** predetermined tool selection data associating that optimal tool selection with the mushroom bed state vector, in the same manner as described above generally. As such, when in performance of the crop management program **232** the processor **210** again encounters that given action, it is operable using the selection library manager **284** to access the selection library datastore **234**, which now stores the predetermined tool selection data associating that optimal tool selection with the mushroom bed state vector, and thus is operable to use the crop management equipment **300** to perform the given action using that optimal crop management tool **510** as described.

[0056] Additionally, or alternatively, the automated mushroom crop management system **000** may have a plurality of robotic mushroom crop managers **100**A, **100**B . . . **100**N communicatively coupled with a mushroom crop management tool coordinator **700** via a network **900**. An embodiment of the mushroom crop management tool coordinator **700** is shown in FIG. **8**. The mushroom crop management tool coordinator **700** may have a processor **710**, a memory **720**, a storage **730**, a communications interface **740**, and input/output equipment **750**. The memory **720** may store instructions operable by the processor **710** using the storage **730**, the communications interface **740**, and the input/output equipment **750** to perform the functions described herein. In particular, the memory **720** may store a selection request processor **722**, and a library submission processor **724**.

[0057] As described above, each robotic mushroom crop manager controller **200** may be operable to use its selection library manager **284** to determine when an optimal tool selection threshold is met for a given one of the plurality of crop management tools **510**A, **510**B . . . **510**N in association with a given action in the crop management program and a given preconfigured ranges of the properties and characteristics of the mushroom bed **400**. As described above, the selection library manager **284** may store in a selection library datastore **234** predetermined tool selection data associating the predetermined optimal one of the plurality of crop management tools **510**A, **510**B . . . **510**N with the given action included in the crop management program and the preconfigured combination of preconfigured ranges of the the properties and characteristics of the mushroom bed **400**. In such case, processor **210** may further be operable to use the communication interface **240** to transmit to the mushroom crop management tool coordinator **700** a library submission request encoding the predetermined tool selection data. The processor **710** of the mushroom crop management tool coordinator **700** may be operable to use the communications interface **740** to receive the library submission request, and to use the library submission processor **724** to process the library submission request. In particular, the library submission processor **724** may be operable to determine, as described below, whether to add the predetermined tool selection data encoded in the library submission request to the selection library **732** of the mushroom crop management tool coordinator **700**, for use as further described below.

[0058] Specifically, the mushroom crop management tool coordinator **700** may be operable to receive library submission requests from a plurality of robotic mushroom crop manager controllers **200**, as described. Until a threshold number of library submission requests is met, the processor **710** may be operable to store the received library submission requests in a pending datastore **734** in the storage **730**. The memory **720** may further store a selection library manager **784**, and once the threshold number of library submission requests is met, the processor **710** may be operable to use selection library manager **784** to process the stored library submission requests.

[0059] In particular, each stored library submission request may encode corresponding predetermined tool selection data as described above, associating a predetermined optimal one of the plurality of crop management tools **510**A, **510**B . . . **510**N with a given action and a preconfigured combination of preconfigured ranges of the properties and characteristics of the mushroom bed **400**. The corresponding predetermined tool selection data of the stored library submission requests may agree or disagree in certain respects. For example, the predetermined tool selection data of a first one of the library submission requests, for a given action and a first preconfigured combination of preconfigured ranges of the mushroom bed, may indicate selection of a particular one of the plurality of crop management tools **510**A, **510**B . . . **510**N, while the predetermined tool selection data of a second one of the library submission requests, for the same action and a second preconfigured combination of preconfigured ranges of the mushroom bed which overlaps the first preconfigured combination, may indicate selection of a different one of the plurality of crop management tools **510**A, **510**B . . . **510**N. In other words, the two library submission requests may disagree as to the optimal tool selection where the mushroom bed conditions are otherwise similar within a predefined threshold. Conversely, the predetermined tool selection data of a first one of the library submission requests, for a given action and a first preconfigured combination of preconfigured ranges of the mushroom bed, may indicate selection of a particular one of the plurality of crop management tools **510**A, **510**B . . . **510**N, while the predetermined tool selection data of a second one of the library submission requests, for the same action and a second preconfigured combination of preconfigured ranges of the mushroom bed which overlaps the first preconfigured combination, may indicate selection of the same one of the plurality of crop management tools **510**A, **510**B . . . **510**N. In other words, the two library submission requests may agree as to the optimal tool selection where the mushroom bed conditions are otherwise similar. In general, the stored library submission requests may agree or disagree in this way, within a range of degrees.

[0060] Thus, in order to generate predetermined tool selection data from the stored library submission requests, the mushroom crop management tool coordinator **700** may further store a selection library datastore **732** in the storage **730**. The processor **710** may be operable to use the selection library manager **784** to perform any algorithm on the plurality of library submission requests to generate predetermined tool selection data, based at least in part on the range of degrees of agreement and disagreement of the plurality of library submission requests. For example, the selection library manager **784** may be operable to perform a random sample consensus method on the received library submission data structures. Alternatively, or additionally for an initial preconfigured period, the selection library manager **784** may be operable to generate and store in the selection library datastore **732** predetermined tool selection data as described based on each and every received library submission request. Any suitable arrangement is possible and contemplated.

[0061] In addition, for one or more of the robotic mushroom crop manager **100**A, **100**B . . . **100**N, if and when a given action in the crop management program does not in fact produce an actual outcome within the preconfigured similarity with the desired outcome, as described above, then the processor **210** may be operable to use the communication interface **240** to transmit to the mushroom crop management tool coordinator **700** a library removal request encoding the mushroom bed state vector and tool selection involved in the action. The processor **710** of the mushroom crop management tool coordinator **700** may be operable to use the communications

interface **740** to receive the library removal request, and to use the library submission processor **724** to process the library removal request. In particular, the library submission processor **724** may be operable to determine, as described below, whether to remove from the selection library **732** of the mushroom crop management tool coordinator **700** a record with predetermined tool selection data similar within a preconfigured range to the mushroom bed state vector and tool selection encoded in the library removal request.

[0062] The mushroom crop management tool coordinator **700** may be operable to assist any one or more robotic mushroom crop manager **100** to select one of the plurality of crop management tools **510**A, **510**B . . . **510**N for the performance of an action in the crop management program being performed by that robotic mushroom crop manager **100**. As described above, the processor **210** of each robotic mushroom crop manager **100** may be operable to use the selection library manager **284** to select one of the plurality of crop management tools **510**A, **510**B . . . **510**N when the selection library **234** stores predetermined tool selection data, which may be a record in a look-up table, associating a predetermined optimal one of the plurality of crop management tools **510**A, **510**B . . . **510**N with a given action included in the crop management program and a preconfigured combination of preconfigured ranges of the properties and characteristics of the mushroom bed **400**. And, as described above, the processor **210** may be operable otherwise to use the tool selection model **270** to predict an optimal one of the plurality of crop management tools **510**A, **510**B . . . **510**N for performance of the action based on current mushroom bed data, such as a current mushroom bed state vector, generated by the mushroom bed model **260**. As also described above, the processor **210** may be operable to use the tool selection model **270** or the outcome optimizer **282** to generate a confidence indicator of the selection generated by the tool selection model **270**. When the confidence indictor is less than a preconfigured threshold value, the processor **210** may be operable to generate a tool selection request which encodes an action to be performed by the crop management program engine **222** in accordance with the crop management program and mushroom bed data characterizing a current state of the mushroom bed, which may be or include a current mushroom bed state vector generated by the mushroom bed model **260** as described. The processor **210** may then be operable to use the communications interface **240** to transmit to the tool selection request to the mushroom crop management tool coordinator **700**, and the processor **710** of the mushroom crop management tool coordinator **700** may then use the communications interface **740** to receive it. The mushroom crop management tool coordinator **700** may store in the memory **720** a selection request processor **722** operable by the processor **710** to process the tool selection request.

[0063] In particular, the processor **710** may be operable to use the selection library manager **784** to determine whether the selection library datastore **732** stores predetermined tool selection data, which may be a record in a look-up table, associating a predetermined optimal one of the plurality of crop management tools **510**A, **510**B . . . **510**N associated with a given action and a preconfigured combination of preconfigured ranges of the properties and characteristics of the mushroom bed **400** which overlaps or is similar within a preconfigured threshold to the current state of the mushroom bed as encoded in the tool selection request. If so, then the selection request processor **722** may be operable to generate a tool selection reply identifying the optimal one of the plurality of crop management tools **510**A, **510**B . . . **510**N, and the processor **210** may be operable to use the communications interface **240** to communicate the tool selection reply to the robotic mushroom crop manager **100** which sent the tool selection request.

[0064] Alternatively, the processor **710** using the selection library manager **784** may determine that the selection library datastore **732** does not store predetermined tool selection data associating a predetermined optimal one of the plurality of crop management tools **510**A, **510**B . . . **510**N with the given action and preconfigured combination of preconfigured ranges of the properties and characteristics of the mushroom bed **400** which overlaps or is similar within a preconfigured threshold to the current state of the mushroom bed as encoded in the tool selection request. In such

case, the processor **710** may generate and operate a tool selection model **770** stored in the memory **720**. The tool selection model **770** may be configured and operate substantially similarly to the tool selection model **270** of any one or more of the robotic mushroom crop manager **100**, as described above. For this purpose, the tool selection request received from a robotic mushroom crop manager **100**, as described above, may encode a mushroom bed state vector, and the processor **710** may be operable to use the tool selection model **770** to ingest the mushroom bed state vector and generate a predicted optimal tool selection, in substantially the same manner as described above with the tool selection model **270**. The selection request processor **722** may then be operable to generate a tool selection reply identifying the predicted optimal one of the plurality of crop management tools **510**A, **510**B . . . **510**N, and the processor **210** may be operable to use the communications interface **240** to communicate the tool selection reply to the robotic mushroom crop manager **100** which sent the tool selection request. The processor **710** may also be operable to store in a pending datastore **734** in the storage **730** a record of the optimal tool selection predicted by the tool selection model **770**, in association with the tool selection request encoding the mushroom bed state vector used by the tool selection model **770** to generate the predicted optimal tool selection. The stored predicted tool selection record may be used later to train the tool selection model **770**, as further described below.

[0065] In either case, the processor **210** of the robotic mushroom crop manager **100** that sent the tool selection request may use the communications interface **240** to receive the tool selection reply. The processor **210** may be operable, which may be using the crop management program engine **222** —when a tool selection request has been communicated to the mushroom crop management tool coordinator **700** as described above—to wait for a preconfigured waiting period before performing the action required by the crop management program. The preconfigured waiting period may have any suitable duration, and in different embodiments may be 1 second to 5 minutes (300 seconds), or 2 seconds to 2 minutes (120 seconds), or about 2 seconds. If the tool selection reply is not received by the robotic mushroom crop manager **100** within that preconfigured waiting period, then the processor **210** may be operable to perform the action as described above, which may be to perform the action using the one of the plurality of crop management tools **510**A, **510**B . . . **510**N determined by the tool selection model **270** regardless of the confidence indicator of the selection generated by the tool selection model **270**. Alternatively, if the tool selection reply is not received by the robotic mushroom crop manager **100** within that preconfigured waiting period, then the processor **210** may be operable to perform a next action in the crop management program—that is, to skip the first action, and this may include modification of the crop management program to perform the skipped action at a later time or a later position in the sequence of actions in the crop management program. If the tool selection reply is received by the robotic mushroom crop manager **100** within the preconfigured waiting period, however, then the processor **210** may be operable, which may be using the crop management program engine **222**, to perform the action using the one of the plurality of crop management tools **510**A, **510**B . . . **510**N identified in the tool selection reply.

[0066] If the tool selection reply was generated by the mushroom crop management tool coordinator **700** based on predetermined tool selection data in its selection library datastore **732**, as described above, then the tool selection reply may encode an indicator of such, and once the tool selection reply is received by the robotic mushroom crop manager **100**, the processor **210** may be further operable to use the selection library manager **284** to generate and store in the selection library datastore **234** predetermined tool selection data based on the tool selection reply.

[0067] If the tool selection reply was generated by the mushroom crop management tool coordinator **700** using the tool selection model **770**, as described above, then the tool selection reply may encode an indicator of such. The processor **210** of the robotic mushroom crop manager **100** may then be operable to generate tool selection feedback identifying the selected one of the plurality of crop management tools **510**A, **510**B . . . **510**N identified in the tool selection reply and

encoding the post-action mushroom bed state. The processor **210** may then be operable to use the communications interface **240** to transmit the tool selection feedback to the mushroom crop management tool coordinator **700**, whose processor **710** may then use the communications interface **740** to receive it. The processor **710** may then use the received tool selection feedback to train the tool selection model **770** in substantially the same way as the processor **210** trains the tool selection model **270** as described above, and in particular by using the comparer **780** and outcome optimizer **782** stored in the memory **720**, which are substantially similar to, and function in substantially the same way, as the comparer **280** and outcome optimizer **282** as described above.

[0068] In particular, the processor **710** may be operable to train the tool selection model **770** using any suitable techniques known in the art. A network architecture or topology may be established, and layers may be added which are associated with respective optimization functions, activation functions, and/or loss functions. One or more artificial neural networks may be used, and each may of any suitable type, including without limitation convolutional neural networks, recurrent neural networks, and deep learning neural networks. The tool selection model **770** may involve one or more of the same artificial neural networks, or may involve different artificial neural networks. The tool selection model **770** may include instructions using supervised or unsupervised machine learning, involving identifying and recognizing patterns in the mushroom bed data (in the form of the mushroom bed data vectors) to enable recognition of mushroom bed states of the mushroom bed, and to enable prediction of a selected crop management tool to produce an optimal actual outcome. The mushroom bed data, used to generate mushroom bed state vectors as described, and the differences between the actual and desired outcomes described herein which may be used to train the artificial neural network may be encoded in any suitable manner, such as, without limitation, an N-dimensional tensor, a matrix, or an array. Training may be performed in any suitable manner, and may include iterative training using labeled training data as described herein. Training of the artificial neural network may involve parameters initialized to random values, which are changed with each iteration, using any appropriate algorithm to converge to predetermined values. Such algorithms may include, for example, gradient descent, stochastic gradient descent (SGD), minibatch SGD, nonlinear conjugate gradient, limited-memory Broyden-Fletcher-Goldfarb-Shanno (L-BFGS), or Levenberg-Marquardt (LMA) algorithms. Training of the artificial neural network may employ any appropriate statistical model, which may be a multinomial logistic regression model, a random forest model, a decision tree, a logistic regression model, or a gradient boosting model.

[0069] In substantially the same way as described above, the selection library manager **784** of the mushroom crop management tool coordinator **700** may be operable by the processor **710** to determine when, for a given predicted optimal tool selection of the plurality of crop management tools **510**A, **510**B . . . **510**N generated by the tool selection model **770**, an optimal tool selection threshold is met for a given action in the crop management program and given preconfigured ranges of the properties and characteristics of the mushroom bed **400**, which may be preconfigured ranges of dimensions of a current mushroom bed state vector, and to generate and store in the selection library datastore **732** predetermined tool selection data, which may be a record in a look-up table, associating the predicted optimal one of the plurality of crop management tools **510**A, **510**B . . . **510**N with the action included in the crop management program and the preconfigured combination of preconfigured ranges of the properties and characteristics of the mushroom bed **400**. In such case, the processor **710** may be further operable, which may be by using the selection request processor **722** or the library submission processor **724**, to generate a library addition instruction encoding the predicted optimal one of the plurality of crop management tools **510**A, **510**B . . . **510**N with the action included in the crop management program and the preconfigured combination of preconfigured ranges of the properties and characteristics of the mushroom bed **400**. The processor **710** may then be operable to use the communications interface **740** to communicate the library addition instruction to one or more, which may be all, of the robotic

mushroom crop managers **100**A, **100**B . . . **100**N, whose processor **210** may be operable to use the communications interface **240** to receive it, and to use the selection library manager **284** to store in the selection library **234** corresponding predetermined tool selection data.

[0070] Thus, in accordance with the foregoing, a method **600** performable by the robotic mushroom crop manager controller **200** is shown in FIG. **9**. The robotic mushroom crop manager controller **200** may train a mushroom bed model **260** based on collected mushroom bed data and known mushroom bed state vectors in order to recognize properties and characteristics of the mushroom bed **400** including properties and characteristics of mushrooms **410** and optionally growth medium **420** (step **605**). The robotic mushroom crop manager controller **200** may collect mushroom bed data and generate current mushroom bed state vectors using the mushroom bed model **260** (step **610**). The robotic mushroom crop manager controller **200** may perform a crop management program including a sequence of actions to be performed by a crop management device **310**, wherein each action is performed using a selected crop management tool **510** from a plurality of crop management tools **510**A, **510**B . . . **510**N. For each action, the robotic mushroom crop manager controller **200** may access a selection library datastore **234** storing a record encoding predetermined tool selection data associating a predetermined optimal one of the plurality of crop management tools **510**A, **510**B . . . **510**N with the current action and a preconfigured combination of preconfigured ranges of the properties and characteristics of the mushroom bed **400** corresponding to the current mushroom bed state vector (step **615**). If such case, the robotic mushroom crop manager controller **200** may cause the crop management device **310** to select that one of the plurality of crop management tools **510**A, **510**B . . . **510**N and perform the current action on the mushroom bed **400** (step **635**). Otherwise, the robotic mushroom crop manager controller **200** may query selected other robotic mushroom crop managers **100**A, **100**B . . . **100**N for a tool selection (step **620**). If at least one other robotic mushroom crop managers **100**A, **100**B . . . **100**N replies with such a tool selection, then the robotic mushroom crop manager controller **200** may cause the crop management device **310** to select that one of the plurality of crop management tools **510**A, **510**B . . . **510**N and perform the current action on the mushroom bed **400** (step **635**). Otherwise, the robotic mushroom crop manager controller **200** may query the crop management tool coordinator **700** for a tool selection (step **625**). If it replies with such a tool selection, then the robotic mushroom crop manager controller **200** may cause the crop management device **310** to select that one of the plurality of crop management tools **510**A, **510**B . . . **510**N and perform the current action on the mushroom bed **400** (step **635**). Otherwise, the robotic mushroom crop manager controller **200** may query a local tool selection model **270** for a tool selection (step **630**), and then cause the crop management device **310** to select that one of the plurality of crop management tools **510**A, **510**B . . . **510**N and perform the current action on the mushroom bed **400** (step **635**). The robotic mushroom crop manager controller **200** may then proceed to perform the next action in the sequences of actions of the crop management program. In addition, the robotic mushroom crop manager controller **200** may also determine a difference between of the actual outcome of the action with a desired outcome (step **645**). Based on this difference, the robotic mushroom crop manager controller **200** may update its local selection library datastore **234** (step **650**), train its local tool selection model (step **655**), and update the mushroom crop management tool coordinator **700** (step **660**).

[0071] A method **800** may be performable by the mushroom crop management tool coordinator **700**. The mushroom crop management tool coordinator **700** may receive using the communications interface **740** a tool selection query from one of the robotic mushroom crop managers **100**A, **100**B . . . **100**N for a tool selection (step **805**). The processor **710** may use the selection request processor **722** to process the selection query. The processor **710** may use the selection library manager **784** to access the selection library datastore **732** for predetermined tool selection data (step **810**). In particular, the processor **710** query, which may be by using the selection library manager **784**, to query the selection library datastore **732** stored in the storage **730** for a record encoding

predetermined tool selection data associating a predetermined optimal one of the plurality of crop management tools **510**A, **510**B . . . **510**N with the current action encoded in the tool selection query and a preconfigured combination of preconfigured ranges of mushroom bed properties and characteristics corresponding to a current mushroom bed state vector encoded in the selection query. If such case, the processor **710** may generate, which may be by using the selection request processor **722**, a tool selection query reply message encoding the optimal tool selection, and may use the communications interface **740** to communicate the tool selection query reply message to the requesting one of the robotic mushroom crop managers **100**A, **100**B . . . **100**N. Otherwise, the processor **710** may query a local tool selection model **770** for a tool selection (step **815**), and then generate and communicate a tool selection query reply message to the requesting one of the robotic mushroom crop managers **100**A, **100**B . . . **100**N as described above (step **820**). Concurrently or contemporaneously with the foregoing, a method **850** may be performable by the mushroom crop management tool coordinator **700**. The the mushroom crop management tool coordinator **700** may receive, which may be by the processor **710** using the communications interface **840**, an update message from one of the one of the robotic mushroom crop managers **100**A, **100**B . . . **100**N (step **855**). The update message may encode a library submission request, as described above, or tool selection feedback, as described above. The processor **710** may process the update message to determine whether it encodes a library submission request or tool selection feedback. The processor **710** may determine, which may be by using the library submission processor **724**, a reliability of the sending one of the robotic mushroom crop managers **100**A, **100**B . . . **100**N (step **860**), and if the reliability is determined to meet or exceed a preconfigured threshold, the processor **710** may use the selection library manager **784** to generate and store in the selection library datastore **732** a record encoding predetermined tool selection data associating the one of the plurality of crop management tools **510**A, **510**B . . . **510**N, the action performed, and the current mushroom bed state vector encoded in the library submission request (step **865**). The processor **710** may also use the comparer **780** and the outcome optimizer **782** to train the tool selection model **770** based on the tool selection feedback message, as described above, where the tool selection feedback message encodes the action performed, the one of the plurality of crop management tools **510**A, **510**B . . . **510**N used to perform the action, the current mushroom bed state vector, and a difference between of the actual outcome of the action with a desired outcome (step **870**).

[0072] In this way, the automated mushroom crop management system **000**, including the plurality of robotic mushroom crop managers **100**A, **100**B . . . **100**N and the mushroom crop management tool coordinator **700** may be operable collectively to train the tool selection model **770** of the mushroom crop management tool coordinator **700**, and to distribute and share amongst all of the robotic mushroom crop managers **100**A, **100**B . . . **100**N optimal selections of the plurality of crop management tools **510**A, **510**B . . . **510**N for the performance of any one or more crop management program actions performable by crop management equipment **300** of the plurality of robotic mushroom crop managers **100**A, **100**B . . . **100**N, while at the same time optimizing time required to determine the optimal tool selection in any particular case, and optimizing training of automated mushroom crop management system **000** for the determination of such optimal tool selections collectively.

[0073] The robotic mushroom crop manager controller **200** of each of the robotic mushroom crop managers **100**A, **100**B . . . **100**N, and the mushroom crop management tool coordinator **700**, may include any computing and related communications and interface technology useful to perform the functions described herein. Such technology may include one or more computers, one or more servers, a group or groups of multiple servers, or one or mobile computing devices. Each of these may include or use further processing or communications technologies, which may include any number of processors and processor types, such as CPUs, one or more graphics processing units (GPUs), digital signal processors (DSPs), and so forth. In general, each such processor (including processors **210,710**) is operable to execute or perform instructions stored in a memory, including

memories **220**,**720**, respectively. Such memory may include or interface persistent memories, such as storage **230**,**730**. Each such processor may use any communications technology, including communications interfaces **240**,**740**, which may include network interface controllers (NICs), which may be wired or wireless controllers, operable to perform communication over a network, including network **900**, which may be or include the Internet. The robotic mushroom crop manager controller **200** of any one or more of the robotic mushroom crop managers **100**A, **100**B . . . **100**N, and in particular the mushroom crop management tool coordinator **700**, may include or be implemented in part or in whole in a cloud computing environment, including without limitation Amazon AWS™ or Microsoft Azure™.

[0074] The following are non-limiting embodiments of the disclosed subject-matter.

[0075] Embodiment 1. A robotic mushroom crop manager comprising: at least one processor; a communications interface; and at least one computer-readable medium storing instructions executable by the at least one processor to cause the robotic mushroom crop manager: to periodically or continuously receive mushroom bed data corresponding to a mushroom bed including growing mushrooms at a plurality of times; to use a trained mushroom bed model to process the mushroom bed data to generate mushroom bed state vectors respectively characterizing corresponding states of the mushroom bed at the plurality of times; to control crop management equipment to perform a crop management program comprising a sequence of actions to be performed by the crop management equipment comprising, for each current action in the sequence of actions, selecting, based on corresponding a current mushroom bed state vector, a selected crop management tool from a plurality of crop management tools; and to control the crop management equipment to use the selected crop management tool to perform the current action on the mushroom bed.

[0076] Embodiment 2. The robotic mushroom crop manager of Embodiment 1, wherein selecting the selected crop management tool comprises: accessing a selection library datastore storing predetermined tool selection data associating predetermined optimal ones of the plurality of crop management tools with respectively corresponding combinations of actions in the crop management program and preconfigured ranges of the mushroom bed state vectors; for the current action, determining whether the selection library datastore stores predetermined tool selection data wherein the current mushroom bed state vector is similar to one of the preconfigured ranges of the mushroom bed state vectors within a preconfigured threshold; and when, for the current action, the selection library datastore stores predetermined tool selection data wherein the current mushroom bed state vector is similar to one of the preconfigured ranges of the mushroom bed state vectors within the preconfigured threshold, using as the selected crop management tool to perform the current action the optimal one of the plurality of crop management tools identified by the predetermined tool selection data.

[0077] Embodiment 3. The robotic mushroom crop manager of Embodiment 2, wherein selecting the selected crop management tool further comprises: when, for the current action, the selection library datastore is free from predetermined tool selection data wherein the current mushroom bed state vector is similar to one of the preconfigured ranges of the mushroom bed state vectors within the preconfigured threshold, accessing a robotic mushroom crop manager (RMCM) list datastore storing records corresponding respectively to one or more other similar robotic mushroom crop managers, each record storing an identifier and a communication address of the corresponding other similar robotic mushroom crop manager, and selecting one of the other similar robotic mushroom crop managers based on preconfigured selection parameters; generating a tool selection request message encoding in association the current action and the current mushroom bed state vector, and using the communications interface to communicate the tool selection request message to the communication address of the selected one of the other similar robotic mushroom crop managers; when, for the current action, the robotic mushroom crop manager receives from the selected other similar robotic mushroom manager a tool selection reply message corresponding to

the tool selection request message encoding an optimal tool selection, using as the selected crop management tool to perform the current action the optimal one of the plurality of crop management tools identified by the tool selection reply message.

[0078] Embodiment 4. The robotic mushroom crop manager of Embodiment 3, wherein selecting the selected crop management tool further comprises: when, for the current action, the robotic mushroom crop manager does not receive from the selected other similar robotic mushroom manager the tool selection reply message corresponding to the tool selection request message encoding an optimal tool selection within a preconfigured interval, generating a further tool selection request message encoding in association the current action and the current mushroom bed state vector, and using the communications interface to communicate the further tool selection request to a remote crop management tool coordinator; and when, for the current action, the robotic mushroom crop manager receives from the crop management tool coordinator a tool selection reply message corresponding to the further tool selection request message encoding an optimal tool selection, using as the selected crop management tool to perform the current action the optimal one of the plurality of crop management tools identified by the tool selection reply message.

[0079] Embodiment 5. The robotic mushroom crop manager of Embodiment 4, wherein selecting the selected crop management tool further comprises: when, for the current action, the robotic mushroom crop manager does not receive from the crop management tool coordinator the tool selection reply message corresponding to the tool selection request message encoding an optimal tool selection within a further preconfigured interval, using a local trained tool selection model to generate based on the current mushroom bed state vector the selected one of the plurality of crop management tools.

[0080] Embodiment 6. The robotic mushroom crop manager of Embodiment 5, wherein the at least one computer-readable medium further stores instructions executable by the at least one processor to cause the robotic mushroom crop manager: for each current action, to compare a pre-action mushroom bed state vector corresponding to a first time before performance of the current action with a post-action mushroom bed state vector corresponding to a second time after performance of the current action to determine an actual outcome of the current action; to compare the actual outcome of the current action with a predefined desired outcome of the current action based on predefined parameters of the mushroom bed in accordance with the crop management program; and when the actual outcome is similar to the desired outcome within a predefined threshold, to store in the selection library datastore predetermined tool selection data associating the selected one of the plurality of crop management tools used to perform the current action on the mushroom bed with the current action and the pre-action mushroom bed state vector.

[0081] Embodiment 7. The robotic mushroom crop manager of Embodiment 6, wherein the at least one computer-readable medium further stores instructions executable by the at least one processor to cause the robotic mushroom crop manager: when the actual outcome is similar to the desired outcome within the preconfigured threshold, to train the local tool selection model based on the current action on the mushroom bed and the pre-action mushroom bed state vector.

[0082] Embodiment 8. The robotic mushroom crop manager of Embodiment 7, wherein the at least one computer-readable medium further stores instructions executable by the at least one processor to cause the robotic mushroom crop manager: when the actual outcome is similar to the desired outcome within the preconfigured threshold, to generate an update message encoding the selected one of the plurality of crop management tools used to perform the current action on the mushroom bed and the pre-action mushroom bed state vector; and to use the communications interface to communicate the update message to the crop management tool coordinator.

[0083] Embodiment 9. The robotic mushroom crop manager of any one of Embodiments 1 to 8 comprising: a controller comprising: the at least one processor; the communications interface; and the at least one computer-readable medium; and the crop management device comprising: a crop management device operable to perform the sequence of actions on the mushroom bed; and sensors

operable to collect the mushroom bed data, the sensors comprising at least one optimal imager operable to collect images of the mushroom bed.

[0084] Embodiment 10. The robotic mushroom crop manager of Embodiment 9, wherein: the crop management device comprises a robotic arm comprising an end effector operable to selectively couple with each of the plurality of crop management tools to perform each current action using the corresponding selected crop management tool; the at least one optimal imager comprises: a harvesting imager mounted at an underside of the robotic arm proximal the end effector and operable to collect harvesting imager images of a plan or overhead view of the mushroom bed beneath the end effector; a trimming imager mounted at or proximal the robotic arm and oriented and operable to collect trimming imager images of an elevation, side, or perspective view of the end effector and the mushroom bed adjacent the end effector; and the mushroom bed data comprises the harvesting imager images and the trimming imager images.

[0085] Embodiment 11. The robotic mushroom crop manager of Embodiment 10, wherein: the current action comprises harvesting a selected one of the mushrooms; the pre-action mushroom bed state vector is generated based on harvesting imager images of the selected mushroom collected before harvesting of the selected mushroom using the selected one of the crop management tools; the post-action mushroom bed state vector is generated based on harvesting imager images of the selected mushroom after harvesting of the selected mushroom using the selected one of the crop management tools; and the desired outcome comprises a maximum degree of damage to a cap or stem of the selected mushroom.

[0086] Embodiment 12. The robotic mushroom crop manager of Embodiment 11, wherein: the desired outcome further comprises a maximum degree of damage to a cap or stem of other ones of the mushrooms proximal the selected mushroom in the mushroom bed.

[0087] Embodiment 13. The robotic mushroom crop manager of Embodiment 12, wherein: the desired outcome further comprises a maximum degree of disturbance to growing medium in the mushroom bed proximal the selected mushroom.

[0088] Embodiment 14. The robotic mushroom crop manager of any one of Embodiments 1 to 13, wherein: at least some of the crop management tools comprise suction harvesters operable to apply suction to respective heads of at least some of the mushrooms to lift the mushrooms during harvesting.

[0089] Embodiment 15. An automated mushroom crop management system comprising: a plurality of the robotic mushroom crop managers as defined in Embodiment 4 or any one of Embodiments 5 to 14 when dependent on Embodiment 4; and the remote crop management tool coordinator as defined in Embodiment 4, wherein the crop management tool coordinator comprises: at least one further processor; a further communications interface; and at least one further computer-readable medium storing instructions executable by the at least one further processor to cause the crop management tool coordinator: to use the further communications interface to receive the further tool selection request from a requesting robotic mushroom crop manager; to access a further selection library datastore storing predetermined tool selection data associating predetermined optimal ones of the plurality of crop management tools with respectively corresponding actions in the crop management program and preconfigured ranges of the mushroom bed state vectors; for the current action, to determine whether the further selection library datastore stores predetermined tool selection data wherein the current mushroom bed state vector is similar to the preconfigured ranges of the mushroom bed state vectors within a preconfigured threshold; and when, for the current action, the further selection library datastore stores predetermined tool selection data wherein the current mushroom bed state vector is similar to the preconfigured ranges of the mushroom bed state vectors within the preconfigured threshold, to generate the tool selection reply message encoding the optimal tool selection, and using the further communications interface to communicate the tool selection reply message to the requesting robotic mushroom crop manager.

[0090] Embodiment 16. The automated mushroom crop management system of Embodiment 15,

wherein the at least one further computer-readable medium further stores instructions executable by the at least one further processor to cause the crop management tool coordinator: when, for the current action, the further selection library datastore does not store predetermined tool selection data wherein the current mushroom bed state vector is similar to the preconfigured ranges of the mushroom bed state vectors within a preconfigured threshold, to use a further local trained tool selection model to generate the optimal tool selection based on the current mushroom bed state vector; to generate the tool selection reply message encoding the optimal tool selection; and to use the further communications interface to communicate the tool selection reply message to the requesting robotic mushroom crop manager.

[0091] Embodiment 17. The automated mushroom crop management system of Embodiment 16, wherein the at least one further computer-readable medium further stores instructions executable by the at least one further processor to cause the crop management tool coordinator: to store in the further selection library datastore predetermined tool selection data associating the selected one of the plurality of crop management tools used to perform the current action on the mushroom bed with the current action and the pre-action mushroom bed state vector.

[0092] Embodiment 18. The automated mushroom crop management system of Embodiment 17, wherein the at least one further computer-readable medium further stores instructions executable by the at least one further processor to cause the crop management tool coordinator: to train the further local tool selection model based on the current action on the mushroom bed and the pre-action mushroom bed state vector.

[0093] Embodiment 19. A method performed by at least one processor of a robotic mushroom crop manager, the robotic mushroom crop manager comprising a communications interface, the method comprising: periodically or continuously receiving mushroom bed data corresponding to a mushroom bed including growing mushrooms at a plurality of times; using a trained mushroom bed model to process the mushroom bed data to generate mushroom bed state vectors respectively characterizing corresponding states of the mushroom bed at the plurality of times; and controlling crop management equipment to perform a crop management program comprising a sequence of actions to be performed by crop management equipment comprising, for each current action in the sequence of actions: selecting, based on corresponding a current mushroom bed state vector, a selected crop management tool from a plurality of crop management tools; and controlling the crop management equipment to use the selected crop management tool to perform the current action on the mushroom bed.

[0094] Embodiment 20. The method of Embodiment 19, wherein selecting the selected crop management tool comprises: accessing a selection library datastore storing predetermined tool selection data associating predetermined optimal ones of the plurality of crop management tools with respectively corresponding combinations of actions in the crop management program and preconfigured ranges of the mushroom bed state vectors; for the current action, determining whether the selection library datastore stores predetermined tool selection data wherein the current mushroom bed state vector is similar to one of the preconfigured ranges of the mushroom bed state vectors within a preconfigured threshold; and when, for the current action, the selection library datastore stores predetermined tool selection data wherein the current mushroom bed state vector is similar to one of the preconfigured ranges of the mushroom bed state vectors within the preconfigured threshold, using as the selected crop management tool to perform the current action the optimal one of the plurality of crop management tools identified by the predetermined tool selection data.

[0095] Embodiment 21. The method of Embodiment 20, wherein selecting the selected crop management tool further comprises: when, for the current action, the selection library datastore is free from predetermined tool selection data wherein the current mushroom bed state vector is similar to one of the preconfigured ranges of the mushroom bed state vectors within the preconfigured threshold, accessing a robotic mushroom crop manager (RMCM) list datastore

storing records corresponding respectively to one or more other similar robotic mushroom crop managers, each record storing an identifier and a communication address of the corresponding other similar robotic mushroom crop manager, and selecting one of the other similar robotic mushroom crop managers based on preconfigured selection parameters; generating a tool selection request message encoding in association the current action and the current mushroom bed state vector, and using the communications interface to communicate the tool selection request message to the communication address of the selected one of the other similar robotic mushroom crop managers; when, for the current action, the robotic mushroom crop manager receives from the selected other similar robotic mushroom manager a tool selection reply message corresponding to the tool selection request message encoding an optimal tool selection, using as the selected crop management tool to perform the current action the optimal one of the plurality of crop management tools identified by the tool selection reply message.

[0096] Embodiment 22. The method of Embodiment 21, wherein selecting the selected crop management tool further comprises: when, for the current action, the robotic mushroom crop manager does not receive from the selected other similar robotic mushroom manager the tool selection reply message corresponding to the tool selection request message encoding an optimal tool selection within a preconfigured interval, generating a further tool selection request message encoding in association the current action and the current mushroom bed state vector, and using the communications interface to communicate the further tool selection request to a remote crop management tool coordinator; and when, for the current action, the robotic mushroom crop manager receives from the crop management tool coordinator a tool selection reply message corresponding to the further tool selection request message encoding an optimal tool selection, using as the selected crop management tool to perform the current action the optimal one of the plurality of crop management tools identified by the tool selection reply message.

[0097] Embodiment 23. The method of Embodiment 22, wherein selecting the selected crop management tool further comprises: when, for the current action, the robotic mushroom crop manager does not receive from the crop management tool coordinator the tool selection reply message corresponding to the tool selection request message encoding an optimal tool selection within a further preconfigured interval, using a local trained tool selection model to generate based on the current mushroom bed state vector the selected one of the plurality of crop management tools.

[0098] Embodiment 24. The method of Embodiment 23 further comprising: for each current action, comparing a pre-action mushroom bed state vector corresponding to a first time before performance of the current action with a post-action mushroom bed state vector corresponding to a second time after performance of the current action to determine an actual outcome of the current action; comparing the actual outcome of the current action with a predefined desired outcome of the current action based on predefined parameters of the mushroom bed in accordance with the crop management program; and when the actual outcome is similar to the desired outcome within a predefined threshold, storing in the selection library datastore predetermined tool selection data associating the selected one of the plurality of crop management tools used to perform the current action on the mushroom bed with the current action and the pre-action mushroom bed state vector.

[0099] Embodiment 25. The method of Embodiment 24 further comprising: when the actual outcome is similar to the desired outcome within the preconfigured threshold, training the local tool selection model based on the current action on the mushroom bed and the pre-action mushroom bed state vector.

[0100] Embodiment 26. The method of Embodiment 25 further comprising: when the actual outcome is similar to the desired outcome within the preconfigured threshold, generating an update message encoding the selected one of the plurality of crop management tools used to perform the current action on the mushroom bed and the pre-action mushroom bed state vector; and using the communications interface to communicate the update message to the crop management tool

coordinator.

[0101] Embodiment 27. The method of any one of Embodiments 19 to 26, wherein the robotic mushroom crop manager comprises: a controller comprising: the at least one processor; the communications interface; and the at least one computer-readable medium; and the crop management device comprising: a crop management device operable to perform the sequence of actions on the mushroom bed; and sensors operable to collect the mushroom bed data, the sensors comprising at least one optimal imager operable to collect images of the mushroom bed.

[0102] Embodiment 28. The method of Embodiment 27, wherein: the crop management device comprises a robotic arm comprising an end effector operable to selectively couple with each of the plurality of crop management tools to perform each current action using the corresponding selected crop management tool; the at least one optimal imager comprises: a harvesting imager mounted at an underside of the robotic arm proximal the end effector and operable to collect harvesting imager images of a plan or overhead view of the mushroom bed beneath the end effector; a trimming imager mounted at or proximal the robotic arm and oriented and operable to collect trimming imager images of an elevation, side, or perspective view of the end effector and the mushroom bed adjacent the end effector; and the mushroom bed data comprises the harvesting imager images and the trimming imager images.

[0103] Embodiment 29. The method of Embodiment 28, wherein: the current action comprises harvesting a selected one of the mushrooms; the pre-action mushroom bed state vector is generated based on harvesting imager images of the selected mushroom collected before harvesting of the selected mushroom using the selected one of the crop management tools; the post-action mushroom bed state vector is generated based on harvesting imager images of the selected mushroom after harvesting of the selected mushroom using the selected one of the crop management tools; and the desired outcome comprises a maximum degree of damage to a cap or stem of the selected mushroom.

[0104] Embodiment 30. The method of Embodiment 29, wherein: the desired outcome further comprises a maximum degree of damage to a cap or stem of other ones of the mushrooms proximal the selected mushroom in the mushroom bed.

[0105] Embodiment 31. The method of Embodiment 30, wherein: the desired outcome further comprises a maximum degree of disturbance to growing medium in the mushroom bed proximal the selected mushroom.

[0106] Embodiment 32. The method of any one of Embodiment 19 to 31, wherein: at least some of the crop management tools comprise suction harvesters operable to apply suction to respective heads of at least some of the mushrooms to lift the mushrooms during harvesting.

[0107] Embodiment 33. The method of Embodiment 22 or any one of Embodiments 23 to 32 when dependent on Embodiment 22, wherein the crop management tool coordinator comprises a further communications interface, the method further comprising, at the crop management tool coordinator: using the further communications interface to receive the further tool selection request from a requesting robotic mushroom crop manager; accessing a further selection library datastore storing predetermined tool selection data associating predetermined optimal ones of the plurality of crop management tools with respectively corresponding actions in the crop management program and preconfigured ranges of the mushroom bed state vectors; for the current action, to determine whether the further selection library datastore stores predetermined tool selection data wherein the current mushroom bed state vector is similar to the preconfigured ranges of the mushroom bed state vectors within a preconfigured threshold; and when, for the current action, the further selection library datastore stores predetermined tool selection data wherein the current mushroom bed state vector is similar to the preconfigured ranges of the mushroom bed state vectors within the preconfigured threshold, to generate the tool selection reply message encoding the optimal tool selection, and using the further communications interface to communicate the tool selection reply message to the requesting robotic mushroom crop manager.

[0108] Embodiment 34. The method of Embodiment 33 further comprising, at the crop management tool coordinator: when, for the current action, the further selection library datastore does not store predetermined tool selection data wherein the current mushroom bed state vector is similar to the preconfigured ranges of the mushroom bed state vectors within a preconfigured threshold, using a further local trained tool selection model to generate the optimal tool selection based on the current mushroom bed state vector; generating the tool selection reply message encoding the optimal tool selection; and using the further communications interface to communicate the tool selection reply message to the requesting robotic mushroom crop manager.

[0109] Embodiment 35. The method of Embodiment 34 further comprising, at the crop management tool coordinator: storing in the further selection library datastore predetermined tool selection data associating the selected one of the plurality of crop management tools used to perform the current action on the mushroom bed with the current action and the pre-action mushroom bed state vector.

[0110] Embodiment 36. The method of Embodiment 35, further comprising, at the crop management tool coordinator: training the further local tool selection model based on the current action on the mushroom bed and the pre-action mushroom bed state vector.

[0111] Embodiment 37. A computer-readable medium storing instructions executable by the at least one processor to perform the method of any one of Embodiments 19 to 36.

[0112] So that the present disclosure may be more readily understood, certain terms are defined. Unless defined otherwise, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which embodiments of the invention pertain. While many methods and materials similar, modified, or equivalent to those described herein can be used in the practice of the embodiments of the present invention without undue experimentation, the preferred materials and methods are described herein.

[0113] All terminology used herein is for the purpose of describing particular embodiments only, and is not intended to be limiting in any manner or scope. For example, as used in this specification and the appended claims, the singular forms "a," "an" and "the" can include plural referents unless the content clearly indicates otherwise.

[0114] Numeric ranges recited within the specification are inclusive of the numbers defining the range and include each integer within the defined range. Throughout this disclosure, various aspects of this invention are presented in a range format. It should be understood that the description in range format is merely for convenience and brevity and should not be construed as an inflexible limitation on the scope of the invention. Accordingly, the description of a range should be considered to have specifically disclosed all the possible sub-ranges, fractions, and individual numerical values within that range. For example, description of a range such as from 1 to 6 should be considered to have specifically disclosed sub-ranges such as from 1 to 3, from 1 to 4, from 1 to 5, from 2 to 4, from 2 to 6, from 3 to 6, etc., as well as individual numbers within that range, for example, 1, 2, 3, 4, 5, and 6, and decimals and fractions, for example, 1.2, 3.8, 1½, and 4¾. This applies regardless of the breadth of the range.

[0115] The terms "about" or "approximately" as used herein refer to variation in the numerical quantity that can occur, for example, through typical measuring techniques and equipment, with respect to any quantifiable variable, including, but not limited to, mass, volume, time, distance, voltage, and current. Further, given solid and liquid handling procedures used in the real world, there is certain inadvertent error and variation that is likely through differences in the manufacture, source, or purity of the ingredients used to make the compositions or carry out the methods and the like. The terms "about" and "approximately" also encompass these variations. Expressions which combine the terms "about" or "approximately" with one or more bounds of a range refer to a union of the bound modified by the term "about" or "approximately" as described above, and the range having the unmodified bound. Thus, for example, the expression "at least about X" means the union of "at least X" and "about X". Similarly, "at most about Y" means the union of "at most Y"

and "about Y".

[0116] The phrase "and/or," as used herein in the specification and in the claims, should be understood to mean "either or both" of the elements so conjoined, i.e., elements that are conjunctively present in some cases and disjunctively present in other cases. Multiple elements listed with "and/or" should be construed in the same fashion, i.e., "one or more" of the elements so conjoined. Other elements may optionally be present other than the elements specifically identified by the "and/or" clause, whether related or unrelated to those elements specifically identified. Thus, as a non-limiting example, a reference to "A and/or B", when used in conjunction with open-ended language such as "comprising" can refer, in one embodiment, to A only (optionally including elements other than B); in another embodiment, to B only (optionally including elements other than A); in yet another embodiment, to both A and B (optionally including other elements); etc.

[0117] As used herein in the specification and in the claims, "or" should be understood to have the same meaning as "and/or" as defined above. For example, when separating items in a list, "or" or "and/or" shall be interpreted as being inclusive, i.e., the inclusion of at least one, but also including more than one, of a number or list of elements, and, optionally, additional unlisted items. Only terms clearly indicated to the contrary, such as "only one of" or "exactly one of", or when used in the claims, "consisting of" will refer to the inclusion of exactly one element of a number or list of elements. In general, the term "or" as used herein shall only be interpreted as indicating exclusive alternatives (i.e. "one or the other but not both") when preceded by terms of exclusivity, such as "either", "one of", "only one of", or "exactly one of". "Consisting essentially of", when used in the claims, shall have its ordinary meaning as used in the field of patent law.

[0118] Embodiments of the disclosed subject-matter are described herein using the auxiliary verb "may". When used herein, unless required otherwise by the context of usage, the auxiliary verb "may" designates an embodiment of the disclosed subject-matter which possesses the addressed object without requiring necessarily that any other embodiment of the disclosed subject-matter possesses the addressed object. Thus, a statement such as "X may include Y" indicates that the disclosed subject-matter includes embodiments where X includes Y, without requiring that all disclosed embodiments include Y, and without excluding any other embodiments which do not include Y.

[0119] While the disclosed subject-matter may be embodied in many different forms, there are described in detail herein specific embodiments. The present disclosure is an exemplification of the principles of the disclosed subject-matter and is not intended to limit the disclosed subject-matter to the particular embodiments illustrated. Furthermore, the disclosed subject-matter encompasses any possible combination of some or all of the various embodiments mentioned herein. In addition the disclosed subject-matter encompasses any possible combination that also specifically excludes any one or some of the various embodiments mentioned herein.

[0120] In some instances, well-known hardware and software components, modules, and functions are shown in block diagram form in order not to obscure the invention. For example, specific details are not provided as to whether the embodiments described herein are implemented as a software routine, hardware circuit, firmware, or a combination thereof.

[0121] Some of the embodiments described herein include a processor and a memory storing computer-readable instructions executable by the processor. In some embodiments, the processor is a hardware processor configured to perform a predefined set of basic operations in response to receiving a corresponding basic instruction selected from a predefined native instruction set of codes. Each of the modules defined herein may include a corresponding set of machine codes selected from the native instruction set, and which may be stored in the memory.

[0122] Embodiments can be implemented as a software product stored in a machine-readable medium (also referred to as a computer-readable medium, a processor-readable medium, or a computer usable medium having a computer-readable program code embodied therein). The machine-readable medium can be any suitable tangible medium, including magnetic, optical, or

electrical storage medium including a diskette, optical disc, memory device (volatile or non-volatile), or similar storage mechanism. The machine-readable medium can contain various sets of instructions, code sequences, configuration information, or other data, which, when executed, cause a processor to perform steps in a method according to an embodiment of the invention. Those of ordinary skill in the art will appreciate that other instructions and operations necessary to implement the described embodiments can also be stored on the machine-readable medium. Software running from the machine-readable medium can interface with circuitry to perform the described tasks.

[0123] In the preceding description, for purposes of explanation, numerous details are set forth in order to provide a thorough understanding of the embodiments. However, it will be apparent to one skilled in the art that these specific details are not required. In particular, it will be appreciated that the various additional features shown in the drawings are generally optional unless specifically identified herein as required. The above-described embodiments are intended to be examples only. Alterations, modifications and variations can be effected to the particular embodiments by those of skill in the art. The scope of the claims should not be limited by the particular embodiments set forth herein, but should be construed in a manner consistent with the specification as a whole.

Claims

1. (canceled)

2. A robotic mushroom crop manager comprising: at least one processor; a communications interface; and at least one computer-readable medium storing instructions executable by the at least one processor to cause the robotic mushroom crop manager; to periodically or continuously receive mushroom bed data corresponding to a mushroom bed including growing mushrooms at a plurality of times; to use a trained mushroom bed model to process the mushroom bed data to generate mushroom bed state vectors respectively characterizing corresponding states of the mushroom bed at the plurality of times; to control crop management equipment to perform a crop management program comprising a sequence of actions to be performed by the crop management equipment comprising, for each current action in the sequence of actions, selecting, based on a corresponding current mushroom bed state vector, a selected crop management tool from a plurality of crop management tools, wherein selecting the selected crop management tool comprises: accessing a selection library datastore storing predetermined tool selection data associating predetermined optimal ones of the plurality of crop management tools with respectively corresponding combinations of actions in the crop management program and preconfigured ranges of the mushroom bed state vectors; for the current action, determining whether the selection library datastore stores predetermined tool selection data wherein the current mushroom bed state vector falls within one of the preconfigured ranges of the mushroom bed state vectors; and when, for the current action, the selection library datastore stores predetermined tool selection data wherein the current mushroom bed state vector falls within one of the preconfigured ranges of the mushroom bed state vectors, using as the selected crop management tool to perform the current action the optimal one of the plurality of crop management tools identified by the predetermined tool selection data; and to control the crop management equipment to use the selected crop management tool to perform the current action on the mushroom bed.

3. The robotic mushroom crop manager of claim 2, wherein selecting the selected crop management tool further comprises: when, for the current action, the selection library datastore is free from predetermined tool selection data wherein the current mushroom bed state vector falls within one of the preconfigured ranges of the mushroom bed state vectors, accessing a robotic mushroom crop manager (RMCM) list datastore storing records corresponding respectively to one or more other like robotic mushroom crop managers, each record storing an identifier and a communication address of the corresponding other like robotic mushroom crop manager, and

selecting one of the other like robotic mushroom crop managers based on preconfigured selection parameters; generating a tool selection request message encoding in association the current action and the current mushroom bed state vector, and using the communications interface to communicate the tool selection request message to the communication address of the selected one of the other like robotic mushroom crop managers; when, for the current action, the robotic mushroom crop manager receives from the selected other like robotic mushroom manager a tool selection reply message corresponding to the tool selection request message encoding an optimal tool selection, using as the selected crop management tool to perform the current action the optimal one of the plurality of crop management tools identified by the tool selection reply message.

4. The robotic mushroom crop manager of claim 3, wherein selecting the selected crop management tool further comprises: when, for the current action, the robotic mushroom crop manager does not receive from the selected other like robotic mushroom manager the tool selection reply message corresponding to the tool selection request message encoding an optimal tool selection within a preconfigured interval, generating a further tool selection request message encoding in association the current action and the current mushroom bed state vector, and using the communications interface to communicate the further tool selection request to a remote crop management tool coordinator; and when, for the current action, the robotic mushroom crop manager receives from the crop management tool coordinator a tool selection reply message corresponding to the further tool selection request message encoding an optimal tool selection, using as the selected crop management tool to perform the current action the optimal one of the plurality of crop management tools identified by the tool selection reply message.

5. The robotic mushroom crop manager of claim 4, wherein selecting the selected crop management tool further comprises: when, for the current action, the robotic mushroom crop manager does not receive from the crop management tool coordinator the tool selection reply message corresponding to the tool selection request message encoding an optimal tool selection within a further preconfigured interval, using a local trained tool selection model to generate based on the current mushroom bed state vector the selected one of the plurality of crop management tools.

6. The robotic mushroom crop manager of claim 5, wherein the at least one computer-readable medium further stores instructions executable by the at least one processor to cause the robotic mushroom crop manager: for each current action, to compare a pre-action mushroom bed state vector corresponding to a first time before performance of the current action with a post-action mushroom bed state vector corresponding to a second time after performance of the current action to determine an actual outcome of the current action; to compare the actual outcome of the current action with a predefined desired outcome of the current action based on predefined parameters of the mushroom bed in accordance with the crop management program; and when a difference between the actual outcome and the desired outcome falls within a predefined threshold, to store in the selection library datastore predetermined tool selection data associating the selected one of the plurality of crop management tools used to perform the current action on the mushroom bed with the current action and the pre-action mushroom bed state vector.

7. The robotic mushroom crop manager of claim 6, wherein the at least one computer-readable medium further stores instructions executable by the at least one processor to cause the robotic mushroom crop manager: when a difference between the actual outcome and the desired outcome falls within the preconfigured threshold, to train the local tool selection model based on the current action on the mushroom bed and the pre-action mushroom bed state vector.

8. The robotic mushroom crop manager of claim 7, wherein the at least one computer-readable medium further stores instructions executable by the at least one processor to cause the robotic mushroom crop manager: when a difference between the actual outcome and the desired outcome falls within the preconfigured threshold, to generate an update message encoding the selected one of the plurality of crop management tools used to perform the current action on the mushroom bed

and the pre-action mushroom bed state vector; and to use the communications interface to communicate the update message to the crop management tool coordinator.

9. The robotic mushroom crop manager of claim 2 comprising: a controller comprising: the at least one processor; the communications interface; and the at least one computer-readable medium; and the crop management equipment comprising: a crop management device operable to perform the sequence of actions on the mushroom bed; and sensors operable to collect the mushroom bed data, the sensors comprising at least one optimal imager operable to collect images of the mushroom bed.

10. A robotic mushroom crop manager comprising: at least one processor; a communications interface; and at least one computer-readable medium storing instructions executable by the at least one processor to cause the robotic mushroom crop manager: to periodically or continuously receive mushroom bed data corresponding to a mushroom bed including growing mushrooms at a plurality of times; to use a trained mushroom bed model to process the mushroom bed data to generate mushroom bed state vectors respectively characterizing corresponding states of the mushroom bed at the plurality of times; to control crop management equipment to perform a crop management program comprising a sequence of actions to be performed by the crop management equipment comprising, for each current action in the sequence of actions, selecting, based on a corresponding current mushroom bed state vector, a selected crop management tool from a plurality of crop management tools; and to control the crop management equipment to use the selected crop management tool to perform the current action on the mushroom bed; a controller comprising: the at least one processor; the communications interface; and the at least one computer-readable medium; and the crop management equipment comprising: a crop management device operable to perform the sequence of actions on the mushroom bed; and sensors operable to collect the mushroom bed data, the sensors comprising at least one optimal imager operable to collect images of the mushroom bed; wherein: the crop management device comprises a robotic arm comprising an end effector operable to selectively couple with each of the plurality of crop management tools to perform each current action using the corresponding selected crop management tool; the at least one optimal imager comprises: a harvesting imager mounted at an underside of the robotic arm adjacent the end effector and operable to collect harvesting imager images of a plan or overhead view of the mushroom bed beneath the end effector; a trimming imager mounted at or adjacent the robotic arm and oriented and operable to collect trimming imager images of an elevation, side, or perspective view of the end effector and the mushroom bed adjacent the end effector; and the mushroom bed data comprises the harvesting imager images and the trimming imager images.

11. The robotic mushroom crop manager of claim 10, wherein: the current action comprises harvesting a selected one of the mushrooms; the pre-action mushroom bed state vector is generated based on harvesting imager images of the selected mushroom collected before harvesting of the selected mushroom using the selected one of the crop management tools; the post-action mushroom bed state vector is generated based on harvesting imager images of the selected mushroom after harvesting of the selected mushroom using the selected one of the crop management tools; and the desired outcome comprises a maximum degree of damage to a cap or stem of the selected mushroom.

12. The robotic mushroom crop manager of claim 11, wherein: the desired outcome further comprises a maximum degree of damage to a cap or stem of other ones of the mushrooms adjacent the selected mushroom in the mushroom bed.

13. The robotic mushroom crop manager of claim 12, wherein: the desired outcome further comprises a maximum degree of disturbance to growing medium in the mushroom bed adjacent the selected mushroom.

14. The robotic mushroom crop manager of claim 2, wherein: at least some of the crop management tools comprise suction harvesters operable to apply suction to respective heads of at least some of the mushrooms to lift the mushrooms during harvesting.

15. An automated mushroom crop management system comprising: a plurality of the robotic mushroom crop managers, each of the plurality of the robotic mushroom crop managers comprising: at least one processor; a communications interface; and at least one computer-readable medium storing instructions executable by the at least one processor to cause the robotic mushroom crop manager; to periodically or continuously receive mushroom bed data corresponding to a mushroom bed including growing mushrooms at a plurality of times: to use a trained mushroom bed model to process the mushroom bed data to generate mushroom bed state vectors respectively characterizing corresponding states of the mushroom bed at the plurality of times; to control crop management equipment to perform a crop management program comprising a sequence of actions to be performed by the crop management equipment comprising, for each current action in the sequence of actions, selecting, based on a corresponding current mushroom bed state vector, a selected crop management tool from a plurality of crop management tools, wherein selecting the selected crop management tool comprises: accessing a selection library datastore storing predetermined tool selection data associating predetermined optimal ones of the plurality of crop management tools with respectively corresponding combinations of actions in the crop management program and preconfigured ranges of the mushroom bed state vectors; for the current action, determining whether the selection library datastore stores predetermined tool selection data wherein the current mushroom bed state vector falls within one of the preconfigured ranges of the mushroom bed state vectors; and when, for the current action, the selection library datastore stores predetermined tool selection data wherein the current mushroom bed state vector falls within one of the preconfigured ranges of the mushroom bed state vectors, using as the selected crop management tool to perform the current action the optimal one of the plurality of crop management tools identified by the predetermined tool selection data: when, for the current action, the selection library datastore is free from predetermined tool selection data wherein the current mushroom bed state vector falls within one of the preconfigured ranges of the mushroom bed state vectors, accessing a robotic mushroom crop manager (RMCM) list datastore storing records corresponding respectively to one or more other like robotic mushroom crop managers, each record storing an identifier and a communication address of the corresponding other like robotic mushroom crop manager, and selecting one of the other like robotic mushroom crop managers based on preconfigured selection parameters; generating a tool selection request message encoding in association the current action and the current mushroom bed state vector, and using the communications interface to communicate the tool selection request message to the communication address of the selected one of the other like robotic mushroom crop managers: when, for the current action, the robotic mushroom crop manager receives from the selected other like robotic mushroom manager a tool selection reply message corresponding to the tool selection request message encoding an optimal tool selection, using as the selected crop management tool to perform the current action the optimal one of the plurality of crop management tools identified by the tool selection reply message when, for the current action, the robotic mushroom crop manager does not receive from the selected other like robotic mushroom manager the tool selection reply message corresponding to the tool selection request message encoding an optimal tool selection within a preconfigured interval, generating a further tool selection request message encoding in association the current action and the current mushroom bed state vector, and using the communications interface to communicate the further tool selection request to a remote crop management tool coordinator; and when, for the current action, the robotic mushroom crop manager receives from the crop management tool coordinator a tool selection reply message corresponding to the further tool selection request message encoding an optimal tool selection, using as the selected crop management tool to perform the current action the optimal one of the plurality of crop management tools identified by the tool selection reply message to control the crop management equipment to use the selected crop management tool to perform the current action on the mushroom bed; and the remote crop management tool coordinator, wherein the crop management tool coordinator

comprises: at least one further processor; a further communications interface; and at least one further computer-readable medium storing instructions executable by the at least one further processor to cause the crop management tool coordinator: to use the further communications interface to receive the further tool selection request from a requesting robotic mushroom crop manager; to access a further selection library datastore storing predetermined tool selection data associating predetermined optimal ones of the plurality of crop management tools with respectively corresponding actions in the crop management program and preconfigured ranges of the mushroom bed state vectors; for the current action, to determine whether the further selection library datastore stores predetermined tool selection data wherein the current mushroom bed state vector falls within the preconfigured ranges of the mushroom bed state vectors; and when, for the current action, the further selection library datastore stores predetermined tool selection data wherein the current mushroom bed state vector falls within the preconfigured ranges of the mushroom bed state vectors, to generate the tool selection reply message encoding the optimal tool selection, and using the further communications interface to communicate the tool selection reply message to the requesting robotic mushroom crop manager.

16. The automated mushroom crop management system of claim 15, wherein the at least one further computer-readable medium further stores instructions executable by the at least one further processor to cause the crop management tool coordinator: when, for the current action, the further selection library datastore does not store predetermined tool selection data wherein the current mushroom bed state vector falls within the preconfigured ranges of the mushroom bed state vectors, to use a further local trained tool selection model to generate the optimal tool selection based on the current mushroom bed state vector; to generate the tool selection reply message encoding the optimal tool selection; and to use the further communications interface to communicate the tool selection reply message to the requesting robotic mushroom crop manager.

17. The automated mushroom crop management system of claim 16, wherein the at least one further computer-readable medium further stores instructions executable by the at least one further processor to cause the crop management tool coordinator: to store in the further selection library datastore predetermined tool selection data associating the selected one of the plurality of crop management tools used to perform the current action on the mushroom bed with the current action and the pre-action mushroom bed state vector.

18. The automated mushroom crop management system of claim 17, wherein the at least one further computer-readable medium further stores instructions executable by the at least one further processor to cause the crop management tool coordinator: to train the further local tool selection model based on the current action on the mushroom bed and the pre-action mushroom bed state vector.

19-**20**. (canceled)