How does life on land affect contemporary atmospheric CO_2?

Most people know that plants use solar energy to convert inorganic CO_2 into long-chain organic molecules, and that this process of ***photosynthesis*** is the base of the food chain on Earth. At first glance then, perhaps "trees are the answer" as the bumper sticker assures us? But of course life and growth are inevitably followed by death and decay, so in the natural order whatever carbon is removed from the atmosphere to make plants is soon replaced by the respiration of herbivores and bacteria.

For plants and soils and animals on land to have a lasting impact on CO_2 requires not just that plants take up some CO_2, but rather that the total amount of carbon stored on land should change. To permanently remove CO_2 from the air, the amount of carbon in biomass and dead material has to increase permanently, and vice versa. Life on land can only remove carbon from the atmosphere if living things grow faster than they decay for a long time.

Yet to the great surprise of many biologists, the ***total amount of living and dead carbon on land has in fact been increasing for decades***, despite some people's efforts to "pave paradise and put up a parking lot." We know that life on land is a sink for atmospheric CO_2 from the rate of CO_2 growth, from the stable isotope ratio of CO_2 gas, and from other data. Ecologists fought with oceanographers and atmospheric scientists for many years about this, but the ice cores settled it in the 1980s. Believe it or not, ***stuff is growing faster than it's dying!***

This is even weirder than it seems. If we were to fertilize a patch of forest and make it grow faster, we would soon have bigger trees but also more dead branches and leaf litter on the forest floor. More soil carbon for microbes and insects in the soil to digest. And pretty soon the respiration from all that microbial decomposition would catch up to the increased photosynthesis. At that point there would be more carbon stored in the ecosystem, but we'd have reached a ***new steady state*** in which the rate of growth was once more equal to the rate of decay. Yet since at least 1960, life on land has been a sink of atmospheric CO_2 nearly every single year.

How can this be? There are ***four leading causes***:

1. CO_2 Fertilization due to rising CO_2 levels in the air
2. Fertilization by nitrogen and other nutrients
3. Abandonment of formerly cleared land (reforestation), and
4. Encroachment of woody plants into the Arctic due to Boreal warming

CO_2 fertilization is easily observed in a test tube or greenhouse. The chemical reactions that fix CO_2 in chloroplasts simply run faster in a high-CO_2 environment as expected from chemical equilibrium concepts. But it's surprising that this plant-level process can be sustained over huge areas over many decades. Most plant growth is limited by other things than CO_2: light, water, nutrients, the length of the frost-free season, pests, disease, etc. Well-watered and pampered greenhouse plants might respond to elevated CO_2 when they are fat and happy, but one expects whole ecosystems to grow at slower rates limited by environmental factors. Outdoor experiments have shown that doubling ambient CO_2 in forests usually produces a temporary burst of growth, but that after a few years the treated plots revert to slower growth as nutrient or other limitations kick in.

As it turns out, people have been helping out with nutrient limitations as well! Plant growth in most natural ecosystems is limited by nitrogen (meaning if we add nitrogen, they grow faster). Since the invention of chemical fertilizers in 1908, we've been converting inert N_2 from the air into bio-available nitrogen and pouring it all over the biosphere. The Green Revolution has allowed us to feed ever-growing numbers of people, but not all the fertilizer has remained in crop fields. Some inevitably blows on the wind and runs off in streams. ***Besides intentional fertilizer, we fix nitrogen in industrial and automobile combustion***: burning air by combining $N_2 + O_2$ to make NO and NO_2 that oxidize in clouds to NO_3. Plumes of dilute Miracle Gro drift downwind of the Ohio Valley, Western Europe, and Eastern Asia. Much of this fixed nitrogen falls onto forests that are already CO_2-fertlized, and they sequester more and more carbon in wood, leaf, and root.

As a teenager in Massachusetts I walked in lush green forests with closed canopies of maple, birch, and beech that hid the sky. Yet deep in those woods were miles and miles of carefully constructed stone walls. Why would somebody go to the trouble of building all those lovely walls? Because that land wasn't a forest in the 19th Century! Nearly all of New England was farms and pastures for centuries, but as agriculture was displaced by industry and then offices, farms were abandoned and the forest regrew. Similar stories of ***agricultural abandonment and forest regrowth*** are told across much of the developed world. Every molecule of wood in Vermont was made from CO_2 molecules.

The Arctic has warmed more than twice as fast as the rest of the world over recent decades as polar ice melts and allows more solar radiation to be absorbed. In many places in Alaska, Canada, northernmost Europe, and Siberia there are 50% more frost-free days each summer than there were 50 years ago. This has allowed ***woody shrubs and trees to invade into land that could previously support only herbaceous tundra***. The woody plants store a lot of organic carbon that used to be CO_2.

All of the big **land sinks come with expiration dates**. Nitrogen fertilizer only makes plants grow faster until the demand is met. Further additions will only make NO3-rich streams. Once the forests of New England have regrown to maturity, the rate of death will catch up as it does for all of us, and those forests will stop sequestering additional CO_2. Making the Arctic a bit warmer can push the treeline north and store carbon in new Boreal Forests, but a lot more warming will melt the permafrost and expose thousands of years' worth of stored carbon to microbial decay. Even CO_2 fertilization will eventually run its course, though we should probably hope that fraction of the land sink can continue subsidizing our fossil fuel emissions for a few decades to come.